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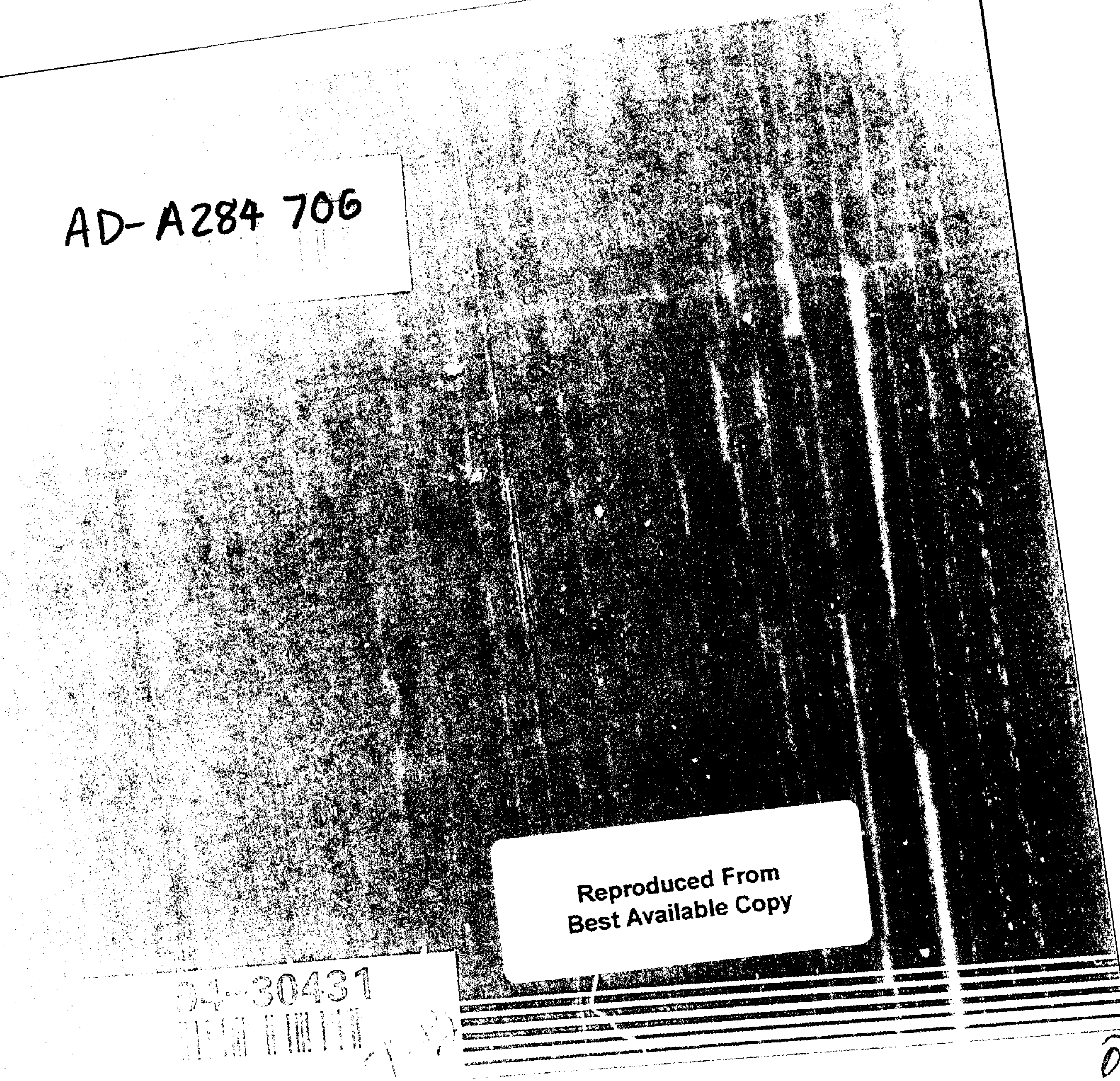

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SLUSH HYDROGEN TECHNOLOGY PROGRAM

FINAL REPORT

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Contract: NAS 3-25420
NASA CR-195353

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This report is submitted to NASA-Lewis Research Center
Cleveland, Ohio in accordance with Contract 3-25420

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PREFACE

This Final Report is submitted for completion of Contract NAS3-25420. The period of performance of this contract was from June 1988 to October 1990. The work was performed by the contractor team of McDonnell Douglas Aerospace (MDA), Martin Marietta Aerospace Group (MMAG), and Air Products and Chemicals, Inc. (APCI) for the NASA-Lewis Research Center (NASA-LeRC). The MDA Program Manager was Mr. Edwin C. Cady. The NASA-LeRC Program Manager was Mr. G. Paul Richter. The contractor team responsibilities were as follows:

MDA: Program Management; STF design ; pre-STF testing at Norco; data analysis.

MMAG: STF design, procurement, and fabrication; pre-STF subscale testing at MMAG, Denver; support data analysis.

APCI: Design, fabricate, and supply slush hydrogen (SH_2) generator; support SH_2 testing and data analysis.

This contractor team also provided a substantial amount of private resources to help make the Slush Technology Facility (STF) an affordable success; we are grateful for these efforts.

In addition to the contractor team, a NASP SH_2 Technology Advisory Group was constituted and provided direction, advice, and support to the team. The members of the Advisory Group, whose efforts were appreciated, were as follows:

<u>NASP JPO</u>
- Kent Weaver
- Steve Van Horn

<u>NASA-LeRC</u>
- Paul Richter
- Frank Berkopec
- Terry Hardy
- Margaret Whalen
- Richard DeWitt

<u>NIST</u>
- Paul Ludtke
- Roland Voth

<u>Rockwell</u>
- Frank Chandler

<u>General Dynamics</u>
- Glen Yates

<u>McDonnell Douglas</u>
- George Orton
- Ed Cady

<u>Martin Marietta</u>
- John Robinson

<u>Air Products</u>
- Jim Peeples
- Scott Baer

This Advisory Group met at approximately quarterly intervals to provide guidance to the SH_2 technology contract to insure that the plans and test results sought would be responsive to the needs of the government and the NASP contractors.

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1.0 SUMMARY

Efforts to advance the technology base for slush hydrogen (SH_2) were initially pursued under this NASA-Lewis Research Center technology maturation Contract NAS 3-25420, and are continuing under the NASP program.

The overall objective of this contract was to resolve the technical/design issues associated with the use of SH_2 as fuel for the NASP by a comprehensive test program utilizing a large-scale test facility to be developed under contract. Four tasks were initially defined:

TASK I	Design and Fabrication of the Slush Technology Facility (STF)
TASK II	Technology Testing Using SH_2
TASK III	Ground Operations Technology Study
TASK IV	Large Scale SH_2 Production Facility Study

Only Tasks I and II were funded under this contract. The task descriptions for these tasks are as follows:

<u>Task I - Design and Fabrication of the Slush Technology Facility (STF)</u>

The design of the STF allowed maximum flexibility for concurrent testing and employed a subsystem approach to enable early use of the facility. Six subsystems were defined and provided support for studies in production, storage, aging, transfer, pressurization and expulsion, and subscale testing: 1) SH_2 generator, 2) 1.9 m^3 (500 gallon) test tank, 3) 1.273 m^3/sec (2700 CFM) vacuum pump system, 4) transfer subsystem, 5) recycle triple point liquid hydrogen ($TPLH_2$) storage tank and 6) subscale test area. A 45.6 m^3 (12,000 gallon) storage tank was incorporated into the STF. Several components of the STF (e.g. 1.9 m^3 - 500 gallon test tank) already existed and were transported to the test site. Development engineering drawings were prepared for all other components. Vacuum jacketed lines were used for SH_2 transfer.

All elements of the STF were assembled at the MMAG Engineering Propulsion Laboratory (EPL). The new and existing hardware were carefully analyzed to assure their contribution to the STF design resulted in an integrated system that provided quality data. Data acquisition and handling was provided by the existing EPL Data System.

Task II - Technology Testing Using SH_2

Technology testing using SH_2 was to be performed in two stages: initial testing using the existing MDA facility at Norco, California, and testing in the STF. A test plan was prepared for the staged series of tests that was to provide a comprehensive understanding of the fluid and handling properties of SH_2 from production through vehicle distribution and use. This database of properties, characteristics, and techniques was to enable the formulation of:

1. Fluid specification,

2. Standard practices and procedures for handling SH_2,

3. Acceptance test criteria for components to be used with SH_2.

Following approval of test plans by the NASA-LeRC program manager, the SH_2 technology testing was conducted. The initial testing was performed at the MDA SH_2 technology facility at the Wyle Labs site in Norco, California. Wyle Labs supported this testing through a subcontract. Additional early testing was also conducted at MMAG's small-scale glass SH_2 test apparatus. These initial tests were completed in five months, after which the MDA 1.9 m^3 (500 gallon) test tank with LH_2 pump/controller was shipped to MMAG's EPL for integration into the STF.

The detailed test plan for the STF testing incorporated the information learned in the initial testing at Wyle and MMAG. Following design, fabrication, successful checkout of the STF, and STF test plan approval, the SH_2 technology testing was to be conducted at the EPL.

Significant NASP programmatic and fiscal modifications occurred in FY1990. Delays in the government funding activities resulted in delay of FY1990 NASP funding until January 1990. This delay required NASA-LeRC to stop work on the STF in late November 1989 due to expenditure/funding limits. In addition, in early 1990, the NASP program contractors agreed to form a consortium. As a result, the Technology Maturation program, of which this contract was a part, was terminated late in 1990. The technology efforts, including SH_2, which were to be done under the Technology Maturation program, would be done by the contractor team as part of the team work-split. At the time the Technology Maturation contract NAS 3-25420 was terminated, Task I was essentially complete, but Task II STF testing had not quite started. Ultimately, the Task II test program was completed in the summer of 1991 under the MDC NASP contract. As a result, only the early testing under Task II was accomplished under Contract NAS 3-25420, and Tasks III and IV were never funded.

2.0 INTRODUCTION

Slush hydrogen (SH_2) has been investigated as a fuel for advanced aerospace vehicles for over 20 years. In this context, SH_2 is defined as a mixture of solid hydrogen particles in liquid hydrogen (LH_2) at the triple point (13.8 K, 52.8 torr). A slush fraction of 50% means the mixture is 50% solid particles by mass. SH_2 is an attractive fuel for these vehicles because of two attributes: increased density, and increased heat capacity. The density of 50% SH_2 is about 15% higher than normal boiling point (NBP) LH_2, which leads to smaller tank volumes and smaller, less costly vehicles. The heat of fusion of the solid, together with the heat capacity of the liquid from triple point (TP) to NBP, adds about 24% to the cooling (heat of vaporization) capacity of NBP LH_2. The extra heat capacity is available without boiling and potential (venting) loss of LH_2, which leads to reduced quantities of fuel, smaller tanks and smaller, less costly vehicles.

A variety of advanced aerospace vehicles could benefit from use of SH_2 as fuel. The National Aerospace Plane (NASP) is the ideal vehicle to use SH_2 because: 1) it has a very large structure cooling requirement because of flight through the atmosphere; and 2) smaller fuel tanks due to density increases and displaced cooling fluid have a magnifying effect on vehicle size due to drag/propulsion effects. The net effect of these two items results in a SH_2-fueled NASP which may be as much as 30% smaller than a NBP LH_2-fueled NASP.

Along with these advantages, there are a number of system design issues associated with the use of SH_2 as a vehicle fuel. Most of theses issues result from the low vapor pressure of SH_2 (52.8 torr) and its rather low heat of fusion (117.5 J/mol). Five of these design issues are:

1. Pressure control of the vehicle SH_2 tanks during ground hold, flight maneuvers, outflow, circulation for engine/subsystem cooling, and mixing.

2. Efficient use of the SH_2 to condense excess cooling H_2, through SH_2 melting, without excessive SH_2 tank pressure rise.

3. Assured SH_2 fraction (e.g. 50% solid) in the vehicle tanks after loading, upgrading, and mixing operations.

4. Achieving specified SH_2 quality (e.g. 50-60% solid) throughout SH_2 production, aging, storage and transfer.

5. Safe, automated, integrated SH_2 ground storage/vehicle operations at all times.

3.0 TASK I - DESIGN AND FABRICATION OF THE SLUSH TECHNOLOGY FACILITY (STF)

3.1 STF Design Objectives

The basic STF design objective was to provide a slush hydrogen (SH_2) test facility which would allow appropriate tests to resolve the technology issues previously described. The STF should include SH_2 production facilities, ground handling/distribution, simulated vehicle fuel tank, and receiver tank. In addition, the STF should provide the visibility and flexibility of research facilities to allow viewing and measurement of the SH_2 and its behavior.

3.2 STF Description

3.2.1 STF Design Criteria

Criteria for the design of the STF were developed, along with the design approach and details to satisfy these criteria, as shown in Table 3-1. Table 3-1 shows specific design details <u>planned</u> for the STF to satisfy the design criteria. Some of these design details were not carried through in the final STF design. In "SH_2 Production," the entire line "Determine effect of surface area" was deleted. Surface area effects were indirectly determined by operating with 2 or 3 vacuum pumps to change the effective pumping rate per unit area. In "SH_2 Transfer," the 0.1 m (4-in) transfer line, although built, was not actually installed for testing, due to problems in sealing the glass-to-metal joints in the transparent sight glass. The 0.025 m (one-inch) diameter transfer line to the 500-gallon test tank was increased in size to 0.05m (two-inch) diameter. In "Pressurization/ Expulsion" the line to "Vary pressurant diffuser configuration" was deleted; the existing test tank diffuser was to be used for all tests. In "Loading/Upgrading" many of the operational techniques described were not actually used during testing, but the capability to perform these operations was designed into the STF.

3.2.2 Overall STF Arrangement

The STF, shown schematically in Figure 3-1, was an integrated system which combined new and existing components to perform system level testing in support of the critical issues for both the ground and aircraft systems for the NASP. The SH_2 GENERATOR SUBSYSTEM consisted of a 4.9 m^3 (1300-gallon) slush generator designed and fabricated by Air Products and Chemicals, Inc. This generator will produce a batch of 2.84 m^3 (750 gallons) (227 kg-500 lbs) of slush at a quality of 50% solid using the freeze-thaw process. The VACUUM SUBSYSTEM for the slush generator consisted of three 0.424 m^3/sec (900 CFM) vacuum pumps combined to provide a

Table 3-1. STF Design Criteria

Criteria	STF Design Approach	STF Design Details to Accomplish
General		
■ SH_2 test tanks allow thermal, pneumatic, hydraulic tests with SH_2	■ Multiple temperature trees • Cryo-diode • MDA thermosensors	■ 1-in sensor spacing in ullage; 6-in spacing in liquid ■ Sensor trees removable from outside tanks
	■ GHe and GH_2 pressurization	■ GHe at 20K (through LH_2HEX); GH_2 at 300K and 80K (LN_2HEX)
	■ Variable speed submersible pump with submerged venturi	■ Pump performance characterized in early Task II testing
	■ Variable diameter test section (sight-glass)	■ 2-in (w/annulus) for slush characteristics, 4-in for flow loss
■ STF quasi-portable	■ All major subsystems mounted on pallet	
■ Test tanks with accessible interiors	■ Interior of all test tanks accessible to allow installation and maintenance	■ Manhole designs for access and plumbing/electrical feed throughs
■ Test tanks vacuum jacketed	■ All tanks vacuum jacketed	■ Slushmaker and TP tank LN_2 shielded; test tank vacuum jacketed w/perlite
SH_2 Production		
■ Freeze-thaw method	■ Slush generator employs freeze-thaw	■ Produces 500 lb of 50% slush
■ Accommodate auger	■ Slush generator accommodates auger	■ 6-in nozzle in slush generator for auger accommodation
■ Determine rate of SH2 production	■ Densitometer to determine production rate	■ Densitometer backed up with melt-back, cap. gage, and H gage
■ Determine effect of surface area	■ Slush generator insert allows surface area variation	■ 42-in insert reduces area by 23%
■ Determine penalty for off-nominal production	■ Pumps varied for off-nominal production	■ 3 x 900 CFM pumps provide greater/less capacity than 2200 CFM nominal required
■ Determine maximum SH_2 fraction attainable		
SH2 Aging		
■ Characterize particle size/shape as a function of age	■ Mixers in SH_2 generator and test tank	■ High performance (LN_2-shielded) tank for aging studies • Variable speed mixer in slush generator • Electric heaters in slush generator
■ Accelerated aging • Heating • Mixing/transfer		
■ Determine maximum SH_2 fraction as a function of age	■ Transfer line sight glass in test section ■ 20 gallon glass Dewars	■ 2-in (w/annulus) transfer line for slush characterization • Possible use of 20 gallon glass Dewars for melt-back

Table 3-1. STF Design Criteria (continued)

Criteria	STF Design Approach	STF Design Details to Accomplish
	SH_2 Transfer	
■ Transfer of SH_2 • Determine solid flow entrainment • Effect of aging on flow loss	■ Variable diameter sight glass	■ 2-in (w/annulus) for entrainment studies, flow loss; 4-in transfer line for flow loss
• Efficient transfer of up to 300 gallons of 50% SH_2	■ MDA slush fraction gage ■ 1-in diameter transfer line to MDA 500 gallon test tank	■ MDA slush fraction gage, cap. gage, melt back
	Pressurization/Expulsion	
■ Pressurize with GHe or GH_2	■ GHe and GH_2 available for pressurization	■ Cold GHe at 20K in LH_2HEX; share with slushmaker
■ Determine pressurant flow rate	■ Flow measurement for GHe and GH_2 by venturi meters	■ Ambient GH_2 at 300K; possibility of 80K (w/LN_2HEX)
■ Determine SH_2 and ullage temperature stratification	■ Temperature trees in test tanks	■ Temperature trees w/1-in spacing (ullage); 6-in spacing (liquid)
	■ Vary pressurant diffuser configuration	■ Alternate diffusers under development
■ Examine ullage pressure collapse due to mixing/sloshing	■ Mixing pumps simulate sloshing	■ Flows up to 400 GPM to simulate sloshing-evaluate in pre-STF testing
	■ Provide ullage pressure measurement	■ External pressure sensors damped against TAO
■ Pump transfer	■ Submersible pump in 500 gallon tank provides pump transfer	■ Provide pumped flow to TP tank
■ Effects of recirculation of hot H_2	■ H_2 submerged diffuser	■ Diffuser design checked out in pre-STF tests
	Loading/Upgrading	
■ Develop loading procedure for X-30 • Loading initially with NBPLH_2 • Upgrading to SH_2 at ~50% • Maintain SH_2 at ~50%	■ Precool lines and 500-gallon test tank with NBPLH_2 ■ Transfer SH_2 to upgrade to 50% SH_2 and maintain ■ Maintain test tank above atmospheric pressure with cold GHe	■ STF schematic arranged to accommodate loading/upgrading • Load 500-gallon test tank with 250 gallons of NBPLH_2 • Pressurize 250 gallon ullage with cold GHe during upgrading • Level sensor required ■ 750-1000 gallon TP tank • Evacuate TP tank to 1.0 psia during loading (minimum control)
■ Verify 50% SH_2 fraction in test tank	■ SH_2 gage in test tank	■ Determine SH_2 quantity required for loading upgrading

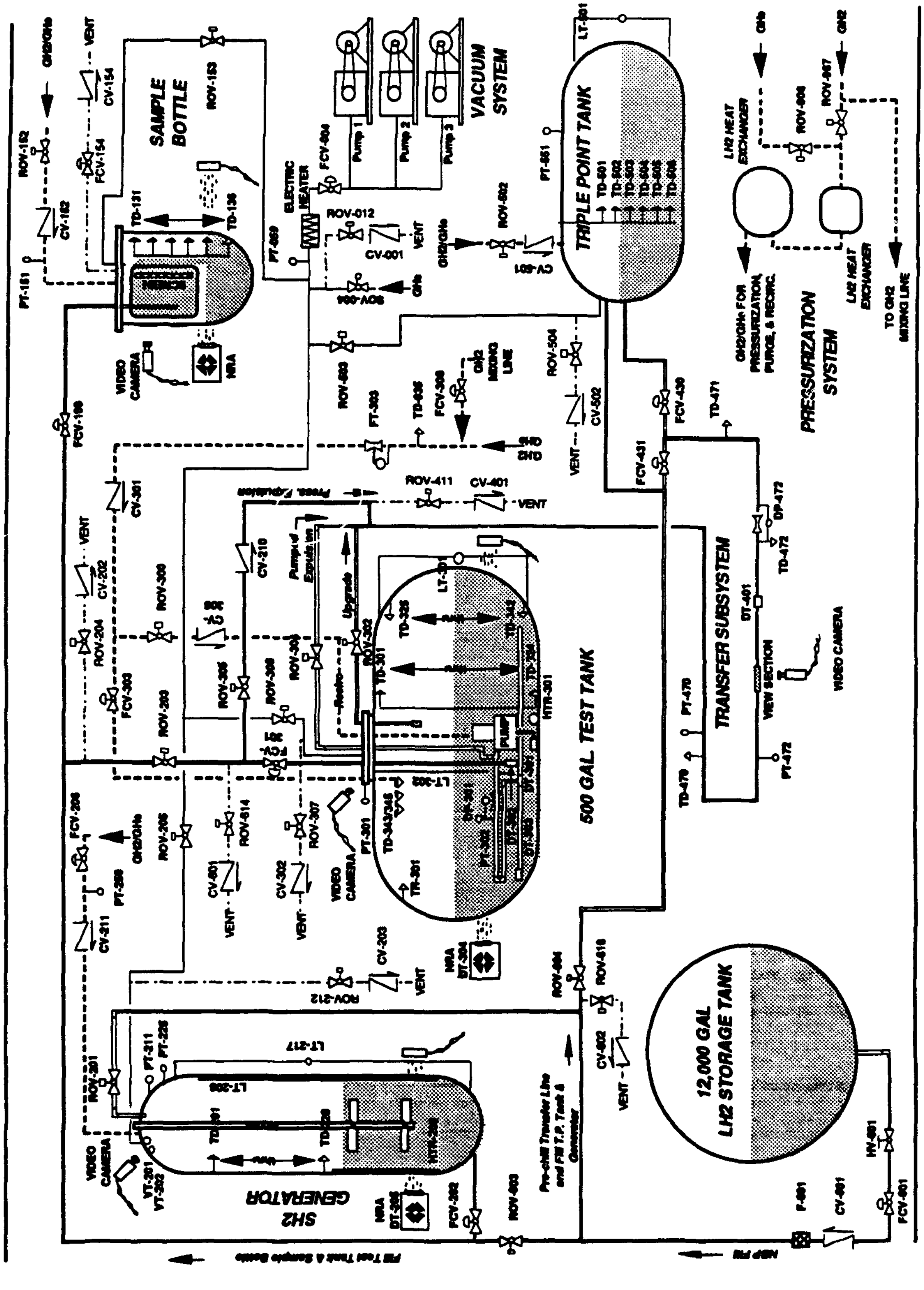


Figure 3-1. Slush Technology Facility (STF) Schematic

nominal capacity of 1.273 m^3/sec (2700 CFM) for the freeze-thaw process. The TEST TANK SUBSYSTEM was an existing 1.9m^3 (500-gallon) Perlite insulated tank provided by MDA. The tank was used as a receiver from the slush generator for loading/upgrading tests and to perform pressurization and outflow tests. The TRANSFER SUBSYSTEM was designed to include a section of removable plumbing and was the area where all dynamic measurements and observations were made (the transfer subsystem includes a transparent section for flow visualization). The TRIPLE POINT TANK was a newly designed 3.8 m^3 (1000-gallon) unit to receive hydrogen liquid from the transfer subsystem and serve as a supply source for TPH_2 to be used in the slush generator during future possible continuous slush production operations. A SAMPLE BOTTLE, consisting of a 0.076 m^3 (20-gallon) glass vacuum jacketed Dewar, was positioned adjacent to the SH_2 generator to allow periodic samples to be taken from the generator during production and aging studies. The PRESSURIZATION SUBSYSTEM consisted of liquid nitrogen (LN_2) and LH_2 heat exchangers to condition the gaseous hydrogen (GH_2) and gaseous helium (GHe) pressurants to temperatures from 20 K to ambient.

3.2.3 Major Component Descriptions

3.2.3.1 Slush Generator

Air Products and Chemicals, Inc. designed and built the slush generator installed at the STF, as well as an identical unit installed at NASA-LeRC Plum Brook Station's K-Site.

The SH_2 generator subsystem was the test bed for slush generation methods and early aging. It also provided the slush used in testing for other subsystems. It was a free-standing subsystem consisting of a slush generating tank and associated hardware. The subsystem was capable of producing slush using the "freeze thaw" method and had the flexibility to allow future testing using the "auger" method.

3.2.3.1.1 Background and Selection of Slush Generator Production Method

Slush hydrogen production is a complex process involving heat and mass transfer. Several basic production technology approaches have been tried by various experimenters. The most thoroughly investigated approach, and one which, in laboratory testing, appeared to generate a slush product suitable for propellant applications, is the freeze-thaw process, which relies upon repetitive fluctuations in pressure around hydrogen's triple point of 52.8 torr (1.02 psia) to create and disperse hydrogen ice crystals.

A potential alternative to the freeze-thaw process, the auger process, utilizes an external refrigeration system to create a film of hydrogen ice on a surface which is then scraped off and dispersed. This process also appears capable of producing propellant grade SH_2, but is much less well understood with regard to critical process and mechanical design variables and the overall energy requirements of the refrigeration and scraper systems.

Other processes (such as liquid spray, cold helium injection, magnetic refrigeration, etc.) have been applied only in very small scale laboratory apparatus, and are not at a stage of technological maturity which would suggest that they are viable candidates for commercial scale production of SH_2 in the near future.

Selection between batch and continuous processes is a function both of the availability of proven technology, and the type of operating environment. Low time-average usage requirements and sporadic patterns of demand (the conditions expected at both the STF and K-Site) when the SH_2 generator is operating as a "utility" supplying SH_2 to storage, transfer, and instrumentation development experiments, suggested that batch production would be more suitable than continuous production. However, the desirability of also utilizing the generators as part of a continuous SH_2 production cycle development program argued against limiting the system to operation in the batch mode only.

The final production mode selection decision was to design a flexible, R&D system in which the generators would be optimized for freeze-thaw batch production operation, but also equipped with additional nozzles and other features which would allow operation in the continuous freeze-thaw production mode as well as permit the installation of an auger for large scale testing of that production technique. In the continuous production mode, the slush generator would be fed $TPLH_2$, and produce up to 50% SH_2. The slush generator is designed to accept a transfer pump and the slush generator vessel has been installed in an elevated position to provide sufficient NPSH for the pump. These features permit the generator to be used for testing large scale production in a continuous mode.

The primary system components (see Figure 3-1) consist of a vacuum pump system, throttling valve, vacuum line heater, slush generator system, storage vessel, vacuum jacketed piping/valves and instruments. The vacuum pumps (which at both the STF and K-Site were selected from available surplus equipment) must attain a nominal vacuum level of 50 torr while maintaining the required evacuation rate for hydrogen vapor removal from the liquid surface. A system heater is included to warm the evacuated hydrogen vapor to near ambient temperature prior to entering the vacuum pump.

3.2.3.1.2 Process Description

The production of 50% SH_2 by the freeze-thaw batch process consists of several steps. These steps include vacuum pumping, freeze-thawing, and aging of the solid hydrogen.

The freeze-thaw production cycle begins with filling the SH_2 generator vessel with $NBPLH_2$. The next step is withdrawal of hydrogen vapor using vacuum pumps. During this evacuation step, a portion of the LH_2 is evaporated, which provides refrigeration for the remaining liquid and which reduces the liquid temperature from the normal boiling point of 20.3 K (36.5°R) to the triple point [P = 52.8 torr (1.02 psia), T = 13.8 K (24.8°R)]. The withdrawn vapor is warmed by a heater prior to entering the vacuum pumps. The vacuum pumps discharge to atmosphere through a vent stack which is purged with nitrogen.

After the temperature of the liquid has reached the triple point, the freeze-thaw portion of the process begins. Through flow control of the vapor, pressure oscillations of approximately 5 torr (0.1 psi) about the triple point pressure are produced. These cause a porous layer of discrete crystalline solids to form at the vapor-liquid interface when the generator pressure is below the triple point. When the flow rate to the vacuum pump is reduced, the pressure rises to (and slightly above) the triple point, causing a film of hydrogen liquid to form on the crystals and allowing them to slide into the liquid. As the mass of solid crystals settles into the liquid region, it fragments and disperses and, with the aid of agitation, creates finely dispersed particles.

The freeze-thaw generator has been designed for an optimum relationship between the vapor-liquid interfacial area and flowrate to the vacuum pumps. This relationship determines the slush particle size by setting the character of the "froth" of solid hydrogen particles formed when vapor erupts from the layer of liquid just below the interface. There is a small range above and below the optimal vapor evolution rate which is suitable for SH_2 production. At the lower end of this range, vapor is withdrawn too slowly causing a "crust" of solid to form, which can bridge the entire surface. When this occurs, the crust will break into unacceptably large chunks by vapor breaking through it. The upper end of the range is marked by vapor erupting so rapidly that it entrains liquid and solid into the suction line to the vacuum pump.

A pressure control valve is used to oscillate the generator pressure about the triple point pressure of hydrogen . The controller setpoint has two modes of oscillation. The first mode is a sinusoidal wave with an adjustable period and amplitude. The second mode is a square wave with an adjustable amplitude period and "freeze" time, where "freeze" time refers to the time when the setpoint is at the low value.

As the percentage of solids in the generator increases above a value in the range of 40% to 50%, depending upon the degree of agitation, solids will begin to protrude above the liquid level, and the production of additional solid hydrogen becomes difficult. "Aging" can be used to increase the solids content of the batch process by providing time for the solids to settle, creating a zone of clarified liquid that can be further freeze-thawed. Aging also results in rounding of individual hydrogen ice crystals, allowing further compaction and decreasing the pressure drop associated with subsequent transfers of the SH_2.

Prior to transfer through pressurization with GHe, the agitator is used to ensure a well mixed slurry. Subsequent experience at Plum Brook indicates that transfer is assisted by downward agitation, as opposed to the upward agitation found to be most suitable during the freeze-thaw portion of the production cycle.

The capability to transfer SH_2 by pumping, instead of by pressurization, was de[illegible] into the generator. If a pump were added to the current system, and other external process a[illegible]tions and changes made, it is estimated that the system, operating in the continuous freeze-thaw production mode, could produce approximately 3860 kg (8500 pounds) per day of 50% solids SH_2.

3.2.3.1.3 Equipment Description

Slush hydrogen is produced in the SH_2 generator vessel. The design of this vessel incorporates several unique features as shown in Table 3-2.

Table 3-2. Slush Vessel Features
• Viewports
• Extractable Mixer
• Vertical Baffles
• Conical Bottom
• Auger Nozzle
• Inlet Pressurization Gas Diffuser
• Heater
• Instrumentation

The slush vessel is constructed utilizing liquid helium technology, namely super insulation and an active liquid nitrogen vapor-cooled shield. The vessel has been designed for a liquid height-to-diameter ratio of 2:1 when containing 227 kg (500 pounds) of 50% SH_2. This was taken as the maximum ratio that will allow mixing of the solids prior to expulsion. On the top head are nozzles for an extractable mixer (large center nozzle), two viewports, fill nozzles for $NBPLH_2$ and $TPLH_2$, future auger installation, pressure relief and instrumentation (capacitance probe and silicon diode temperature rake), as shown in Figure 3-2.

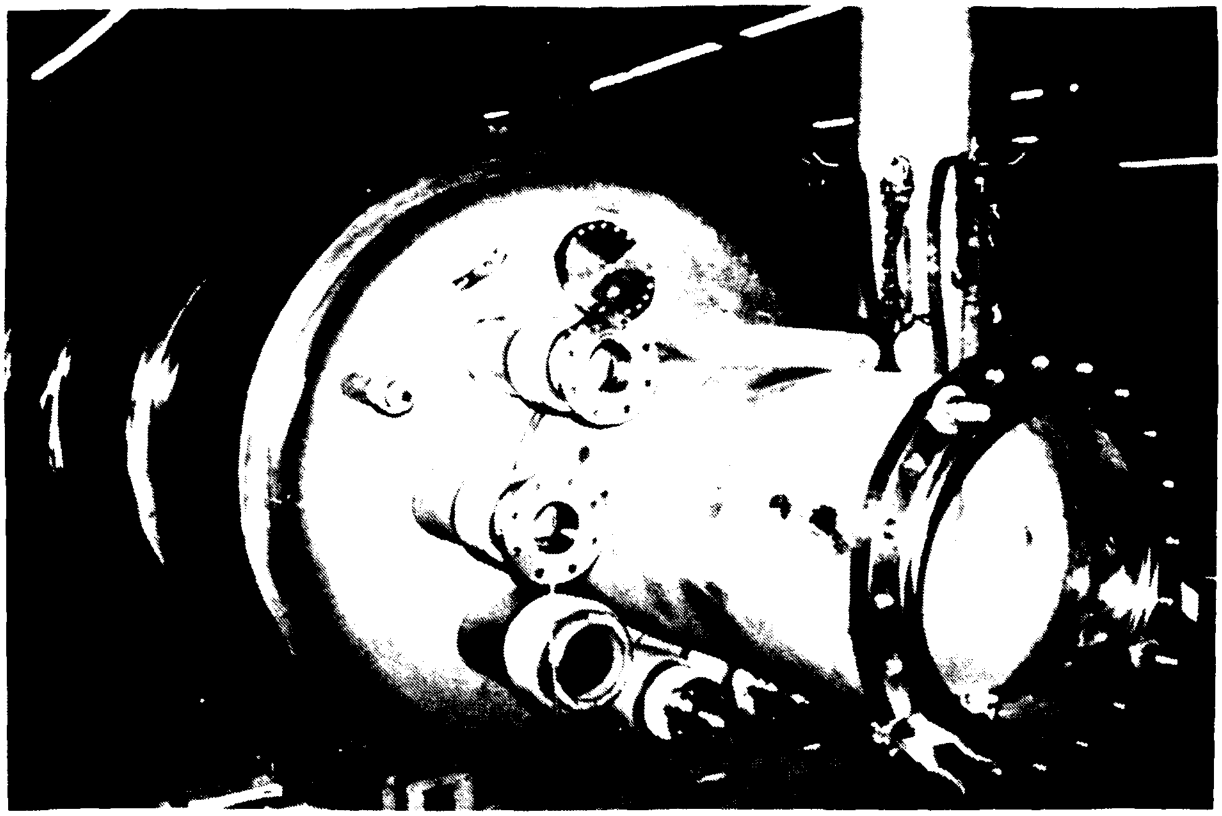


Figure 3-2. View of SH_2 Generator Top Head.

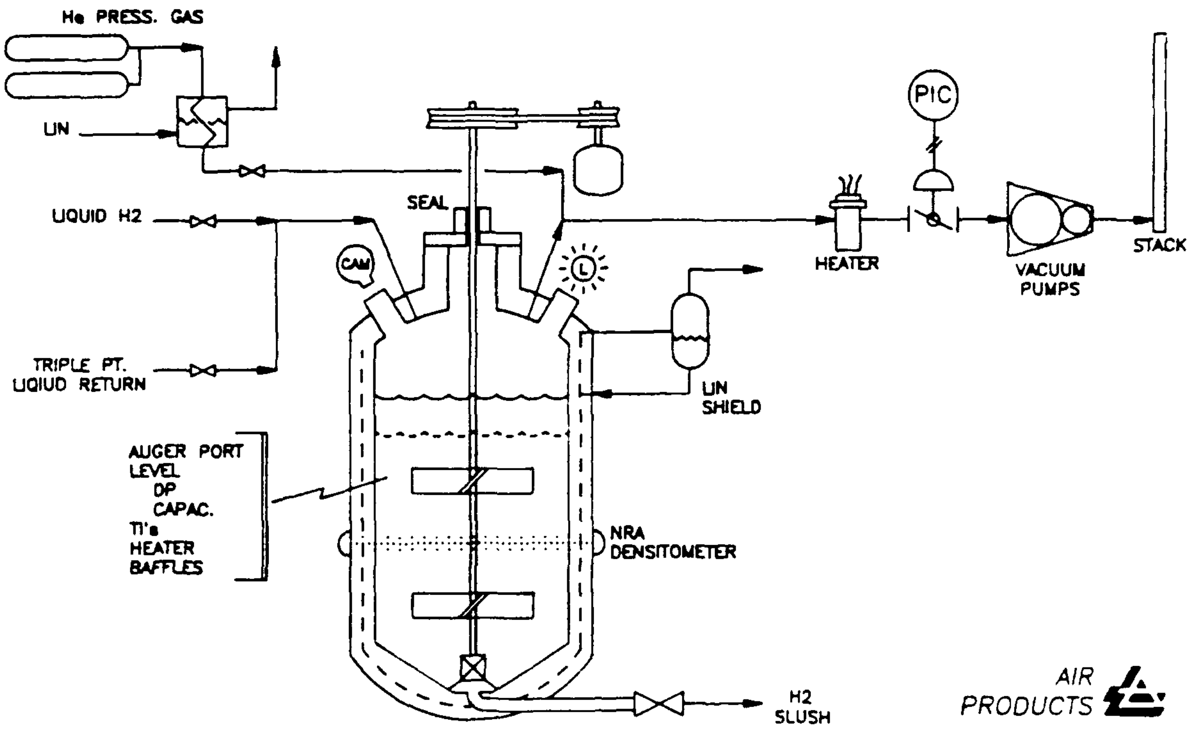


Figure 3-3. SH_2 Generator Process Flow Diagram.

Heating elements are mounted on the inner vessel wall as well as the bottom steady bearing for the mixer centered in the toriconical bottom head. Heaters are placed within the vessel to initially calibrate a gamma ray densimeter which is mounted externally to the generator, and to examine the effects of heat input during the slush aging process. Guides for the capacitance probe and silicon diode temperature rake are also used . Vertical baffles are provided to aid in the suspension of the hydrogen solids in the liquid during mixing. Incorporated within the inner vessel is a toriconical bottom head to aid in the transfer of slush during the expulsion process. An auger service nozzle has been provided to allow for optional auger testing. In addition, an inlet pressurization gas diffuser is provided to ensure uniform pressurization of the vessel during the expulsion process with minimal disruption to the liquid interface. Many of these features are shown in the schematic of Figure 3-3.

Two viewports have been incorporated into the slush generator vessel to permit photographic and television observation of the freeze-thaw and expulsion processes as well as provide visual verification of technical data. A schematic representation of the viewports is shown in Figure 3-4.

The generator viewports utilize a design similar to a previous application developed by NIST, whereby a metal bellows separates the generator tank annular space from the viewports enabling the viewport internals to be serviced without affecting the integrity of the tank vacuum. The cold window consists of a 1.27 cm (one-half inch) thick quartz glass mounted in an invar sleeve which is welded into a vacuum flange. This window is installed from the outside of the tank and is sealed with a copper knife edge gasket. The warm window, consisting of a 1.27 cm (one-half inch) thick Pyrex glass, is sandwiched in the bottom of a pot by an O-ring seal and a Teflon gasket. The warm window pot is also serviceable from outside the tank and is sealed with an O-ring. A 0.64 cm (one-fourth inch) thick Pyrex glass sits on top of a Teflon gasket in contact with the warm window. A porting arrangement enables a purge of nitrogen between the warm window and the cover glass to minimize frosting of the system. Another port to the space between the cold window and the warm window enables this space to be evacuated providing insulation for the system. A vacuum of five microns or lower must be maintained in the space between the cold and warm window to provide sufficient insulation. Figure 3-5 shows the warm and ambient windows being assembled into the cold window bellows assembly. This design approach minimizes heat leak introduced to the process and also enhances safety performance with regards to air in-leakage by monitoring the pressure between the ambient and warm windows.

An extractable mixer is provided in the slush generator vessel. It is designed with an externally serviceable shaft bearing and drive assembly, as well as being variable speed and reversible. These features combined with the variable height feature of the mixer blades provide for flexibility

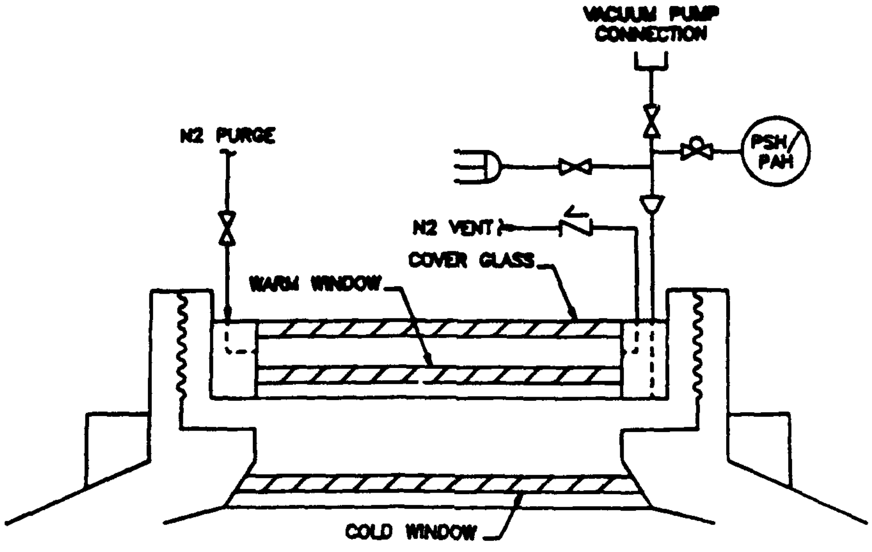


Figure 3-4. View Port Detail.

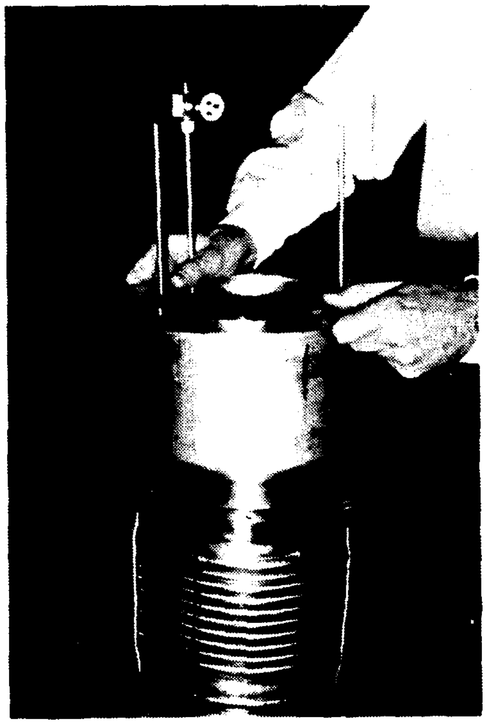


Figure 3-5. View Port Being Assembled.

and optimization of the mixing process. The agitator was scaled based on blade tip velocity from the 0.76 m (30-inch) test work done previously by NBS. A bottom steady bearing has been provided to eliminate any whipping action of the shaft. Figure 3-6 shows the mixer installed in the generator.

The mixer assembly has been designed witha series of seals and purges to eliminate any ingress of oxygen or other contaminants during the subatmospheric phase of generator operation. The slush mixer bearing housing has three seals and two bearings which support the main shaft. The primary seal is a Ferro-fluidics seal, which utilizes a magnetized fluid suspension to seal the vessel from outside air. The other two are grease retaining seals. There is a cavity between the lower grease seal and the Ferro-fluidics seal, which is helium purged and pressurized by a control valve sized to provide enough helium to keep positive pressure in the cavity should the Ferro-fluidics seal fail while the generator is under vacuum. The bottom of the bearing housing (the generator mating flange) is supplied with four electric heaters which are used to keep the Ferro-fluidics seal temperature above freezing. A radiant heat shield collar is provided on the shaft to minimize heat leak in the upper nozzle section as shown in Figure 3-7.

The instrumentation required in this process, in particular for measurement of level, density, and temperature in the slush generator vessel, posed a number of technical challenges. A prerequisite for accurate density measurement is ensuring a representative sample. To accomplish this, mixing of the SH_2 generator vessel contents is necessary to avoid stratification. Density is measured in the vessel through the use of a gamma-ray emitting nuclear radiation attenuation (NRA) densimeter, whose source and detector are both mounted external to the vessel. The gamma-ray emitting nuclear source projects across almost the full diameter of the vessel to measure density across the largest sample possible. This device has a useful density range of 70.5 to 86.5 kg/m^3 (4.4 to 5.4 lb/ft^3)with an expected accuracy of 0.16 kg/m^3 (0.01 lb/ft^3). A heater is installed for densimeter calibration as well as to enhance studies of slush aging and for melting solids if necessary. This heater consists of eight uniformly spaced elements capable of delivering an operator-controlled heat input. Calibration of the densimeter will be accomplished by taking readings of the LH_2 vapor pressure and calculating the density of LH_2 at these conditions. Other calibration points are verified by adding known amounts of heat to known volumes of SH_2 to develop a calibration curve. Specific volume of the slush mixture is generated from level measurements so that the ultimate calibration will depend on the level accuracy.

A continuous level capacitance probe is used to monitor liquid level, primarily during initial liquid fill. A differential pressure transmitter is also used to indicate tank liquid level. Once the slush generation process starts, the capacitance gauge becomes less accurate due to the formation

Figure 3-6. Mixer Installed in the Slush Generator

Figure 3-7. Mixer Heat Shield Configuration.

of solids (which have a different dielectric constant than the liquid). A 30 mesh screen is installed in the bottom of the capacitance plates to prevent solid formation or transport between the plates.

The primary liquid level measurement during slush production is the silicon diode temperature rake. Starting at a point 15.2 cm (six inches) below the 50% slush level in the generator, silicon diodes are mounted at 2.54 cm (one-inch) increments for an elevation of 50.8 cm (20 inches), and then at 5.08 cm (two-inch) increments for an additional 50.8 cm (20 inches). Continuous readout is provided during the slush generation process to measure the critical temperature profile along the rake to within an accuracy of ±0.1°K. A temperature discontinuity will mark the liquid/vapor interface. This silicon diode level measurement system is used in conjunction with an installed electric heater to provide calibration of the densimeter for SH_2. Also, the level may be observed and measured visually via the camera and viewports system.

Air Products designed many components of the slush generator system to be housed in a miscellaneous equipment skid (vacuum line heater, pressure control valve, active LN_2 shield generator vessel cooling system, as well as process vacuum-jacketed piping and other support equipment). This design minimized the field construction effort and provided the smallest possible footprint for the generator system installation. This concept lends itself well to a transportable slush generation system to support future needs of the NASP program, where small quantities of SH_2 may be required.

3.2.3.1.4 Slush Generator Safety Features

Homogeneous SH_2 is a mixture of liquid and solid in equilibrium with vapor at the triple point. The handling of hydrogen at this negative gauge pressure (vacuum) is the major safety-related difference to be recognized when comparing safety considerations appropriate to SH_2 and LH_2. Consequently, the slush generator system incorporates features which preclude leakage of air into the system. The key safety issues addressed in the design of the slush generator system are discussed below.

To ensure maximum personnel safety, the slush generator system is designed to be operated remotely. The viewports, mixer and system instrumentation package allow for effective system control and performance from a remote location.

Several key features are incorporated into the slush generator system to prevent air in-leakage during subatmospheric operation. Relief valves are fitted with rupture discs on their discharge and a helium purge in the space between the disc and valve. Control valve packing allows for a helium purge to avoid air in-leakage. All flanges on the generator vessel have double O-rings and a helium

purge between the rings to prevent air in-leakage. Oxygen concentration is measured in the vacuum subassembly discharge line, prior to the vent. An analyzer with a 0-10 ppm volume range will initiate a system shutdown in the presence of excessive oxygen.

Air Products conducted an exhaustive process hazards review to identify and quantify potential hazards associated with the slush generation process. All recommendations were incorporated into the system process and physical design and verified by an equally intensive design verification hazards review.

3.2.3.1.5 Slush Generator Design Details

The overall design details for the slush generator are summarized in Table 3-3.

Table 3-3. Slush Generator Design Details
(1) 1300 gallon, cylindrical tank (28 ft 4 in height, 48 in I.D., supported on 4 struts
(2) Loaded with 1000 gallons of $NBPLH_2$, final SH_2 quantity is 850 gallons (50% solid by mass)
(3) Vacuum insulated Dewar with an LN_2 nitrogen shield for low heat leak (< 4 Btu/min - static heat leak)
(4) Mixer installed in the generator capable of rotating at approximately 440 rpm. Three blade sections: upper blade near SH_2 surface, middle blade, and kicker blade at the entrance of the outlet line
(5) View Port (8.0 in) and Light Port (8.0 in) installed
(6) Fill Line (1.5 in O.D.), Outlet Line (1.5 in O.D.), Pressurization, Vent and Vacuum Lines, and four additional ports for capacitance gage, electrical and miscellaneous
(7) Instrumentation: NRA Densimeter, 28 diodes (temperature), two level probes (capacitance and Delta P), mixer RPM, two pressure gages (0-50 psia, and 0-2 psia,) mixer vibration sensor, vacuum port (camera and light windows) pressure gage
(8) Manufacturer: Cryenco - Denver, Colorado Manufacturer Serial No.: CRY-502 (built in 1989)
(9) Inlet Remote Actuated Valve (ROV-201), Outlet Flow Control Valve (FVC-202), Vent Valves No. 1 and 2 (ROV-212 and 212A), Vacuum Isolation Valve (ROV-205), Pressurization Supply Valve (FVC-206), SH_2 Supply Valve (ROV-203), Vent Valve (ROV-204)
(10) Heaters installed inside the SH_2 Generator (115 Btu/min)
(11) Maximum Operating Pressure: 40 psig Minimum Operating Temperature: -440°F

The slush generator dimensions and cross-section configuration are shown in Figure 3-8.

3.2.3.2 Vacuum Subsystem

The vacuum subsystem consisted of three 0.424 m^3/sec (900 CFM) Beach Russ vacuum pumps in parallel with 15.2 cm (six-in) diameter piping connecting the pumps independently to each major pressure vessel: the slush generator, the 1.9 m^3 (500-gallon) test tank, the 3.8 m^3 (1000-gallon) triple point tank, and the 0.076 m^3 (20-gallon) sample bottle. The vacuum line to

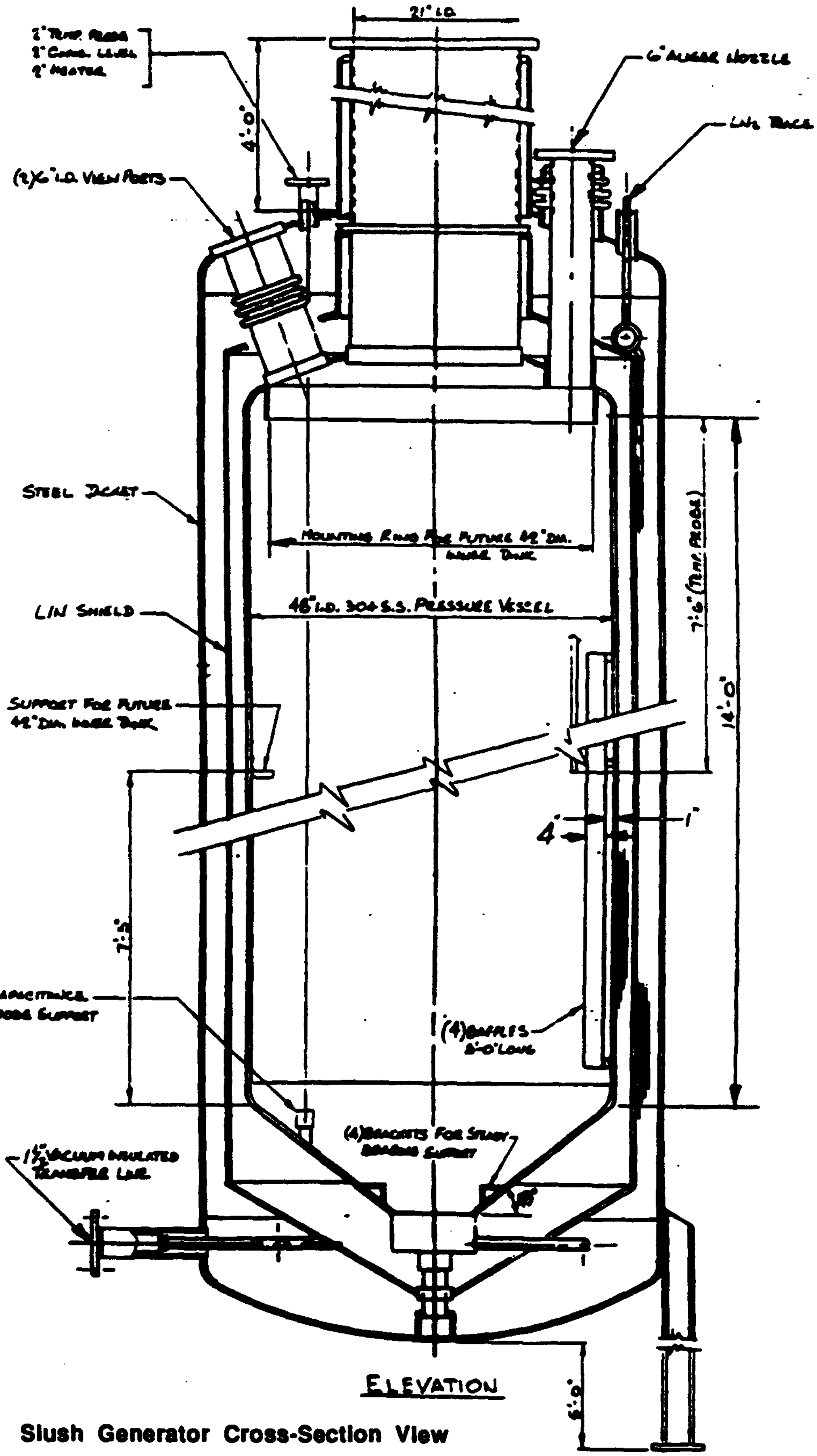


Figure 3-8. Slush Generator Cross-Section View

each of these vessels included valves so that these vessels could be selectively evacuated. The Air Products' supplied electric heater for the evacuated hydrogen was installed in the vacuum line to warm up the hydrogen prior to reaching the vacuum pumps to assure that the pumps did not freeze.

The vacuum control valve, FCV-004, was located downstream of the heater. This valve was used to control the vacuum cycle for pumpdown of the slush generator and slush production. During pumpdown, the valve is essentially wide open, except at start of pumpdown when its position has to be modulated to prevent freezing the vacuum pumps. The initial unconstrained pumpdown hydrogen flow is too high to be warmed up in the heater. After a few minutes, the FCV-004 valve can be opened wide.

During slush production the valve is controlled to a set open/close time by a controller in the blockhouse. The controller can also be used to cycle the valve for a set period and close the valve for a set period, as required for aging in the slush generator.

3.2.3.3 1.9m^3 (500-Gallon) Test Tank and Submerged Pump

3.2.3.3.1 Background

The MDA-supplied 1.9 m^3 (500-gallon) test tank was originally built in the 60's for liquid fluorine service. The tank had an internal coiled-tube heat exchanger which circulated LN_2 to keep the liquid fluorine vent free. This heat exchanger was suspended from the manhole cover into the tank, and was removed when the tank was to be used for SH_2 service. A submerged pump was installed in the tank bottom and outflow plumbing (described below) was suspended from the manhole cover in place of the heat exchanger. The tank and pump were used for SH_2 testing under MDA Independent Research and Development (IRAD) programs prior to the Pre-STF tests described in Section 4.1 and subsequent installation into the STF.

3.2.3.3.2 Test Tank Description

The configuration of the test tank is shown in Figure 3-9. The tank is horizontally mounted and holds 1.9 m^3 (500 gallons) when filled to a level of 0.91m (36 inches) which is approximately the level of the pressurization diffuser/vent line. The tank is vacuum-jacketed with the 0.3 m (12 inch) vacuum annulus filled with perlite insulation. This insulation limits the external heat leak into the tank to about 350 watts. The inner vessel is connected to the outer vessel by bottom supports and a large bellows at the 0.46 m (18-inch) manhole opening to accommodate differential contraction of the inner vessel. The tank is skid-mounted to be movable.

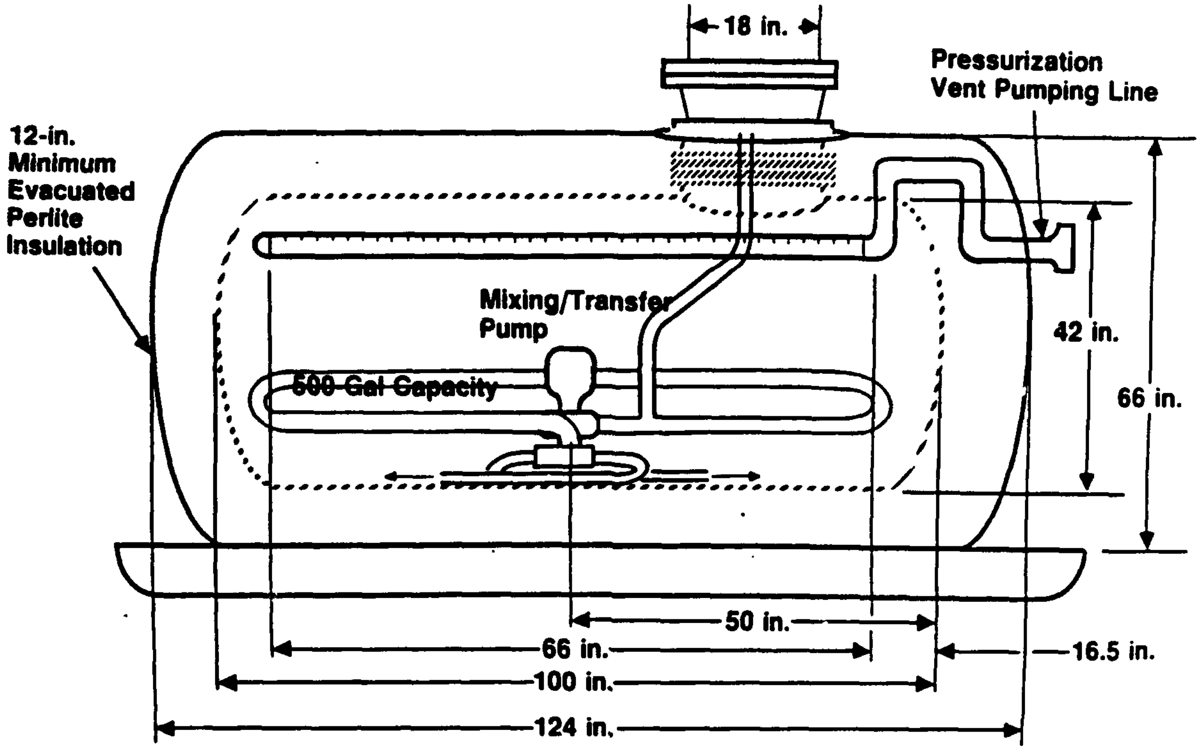


Figure 3-9. 1.9m^3 (500-Gallon) Test Tank Configuration

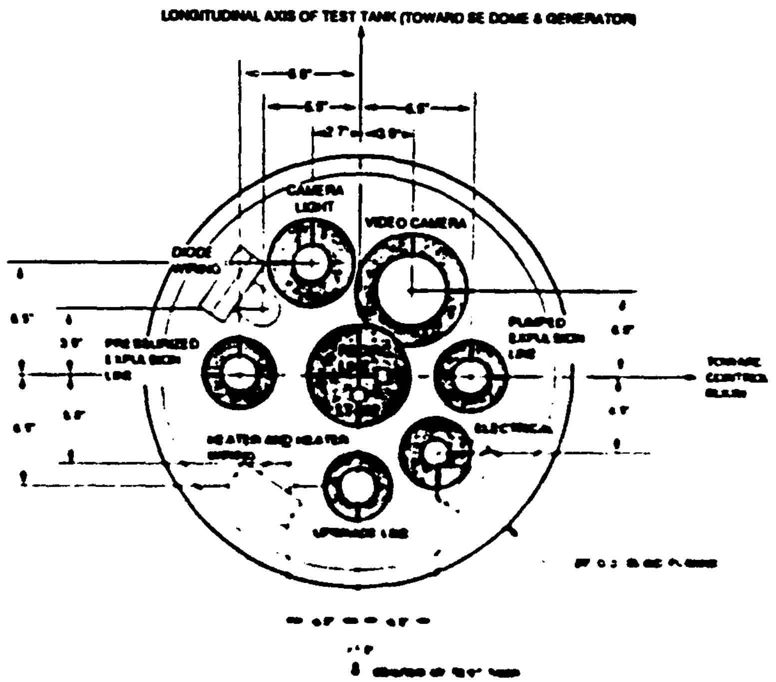


Figure 3-10. Layout of the Test Tank Manhole Cover

The final manhole cover layout is shown in Figure 3-10. The original manhole cover layout used in the Pre-STF testing (see Section 4.1) was different and did not include the upgrade line or the recirculation lines. A new manhole cover was built when the tank was installed at the STF. An evacuated plug attached to the manhole cover was inserted in the manhole to reduce heat leak to the SH_2. Plumbing, instrumentation and viewing tubes were integrated with this plug, and are shown in Figure 3-11. Visible in the figure are the pressurized expulsion (and fill) line (in the foreground with the Simmonds capacitance SH_2 meter on the bottom), the upgrade line (in the background with the screened inlet), the pumped expulsion line fitting (at the top of the plug), the heater system (tubing coils at the left of the figure) and the capacitance probe, temperature sensor rake, recirculation tube and miscellaneous plumbing.

The test tank had a design operating pressure of 483 kPa (70 psig). Safety aspects of the tank system design are discussed below in Section 3.3.2. The pressurant diffuser/tank vent line shown in Figure 3-9 consisted of a horizontal 5 cm (2 inch) diameter tube with 0.64 cm (0.25-inch) slots cut in the top. There were pressure sensing ports at the top and bottom of the inner vessel to be used for head (depth) measurement.

The heater coils (shown in Figure 3-11) were added to the tank after the Pre-STF tests when the test tank was moved to the STF. The heater was used for additional heating during the upgrading and SH_2 maintenance tests.

3.2.3.3.3 Instrumentation

The test tank was heavily instrumented with a full spectrum of temperature, pressure, density, flow, level, and slush fraction sensors as shown previously in Figure 3-1. The temperature sensors included one germanium resistance thermometer (GRT) at the bottom of the tank and silicon diodes for all other temperature sensors. Twenty-four diodes were installed on a rake (Figure 3-11) at 10 cm (4-inch) intervals at the bottom of the tank and at 2.5 cm (1-inch) intervals in the ullage. An additional 18 diodes were positioned around half the tank circumference on the tank wall at 10 cm (4-inch) intervals. Additional diodes were placed on the pressurant diffuser. Pressure sensors were installed to determine tank pressure as well as pump outlet pressure and delta-P for pump flow measurement, and level (head) sensing. Enthalpy meters, to measure (flowing) SH_2 density or solid fraction, were placed at the pump inlet and one of the two mixing outlets (see Figure 3-12). These meters are described in more detail in Section 3.2.3.8. Two other SH_2 density or solid fraction gages were used in the test tank: a Simmonds capacitance type SH_2 density meter in the pressurized outflow/inflow line, and a nuclear radiation attenuation (NRA) density gage, attached to the outside of the test tank. These meters are also discussed in more

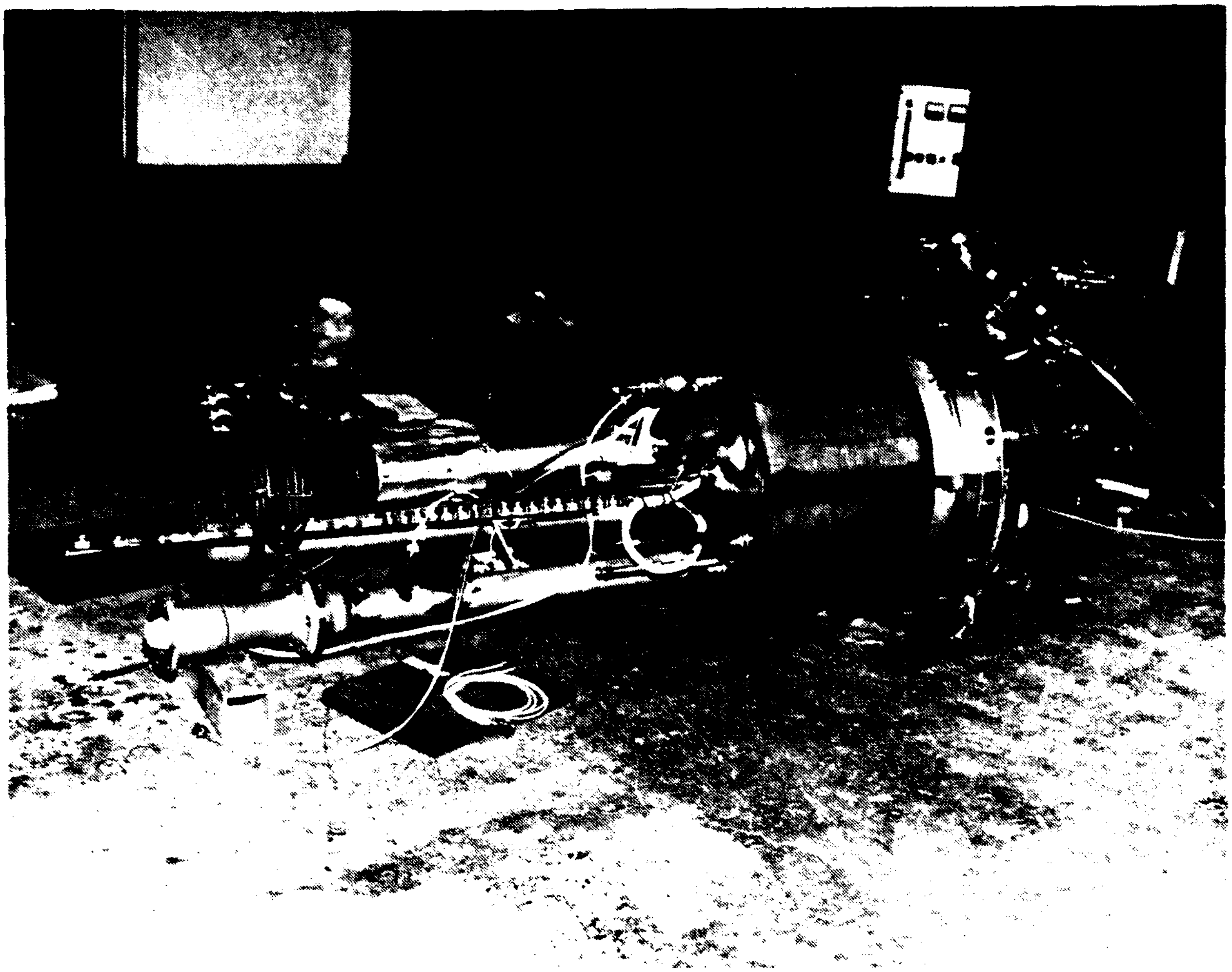
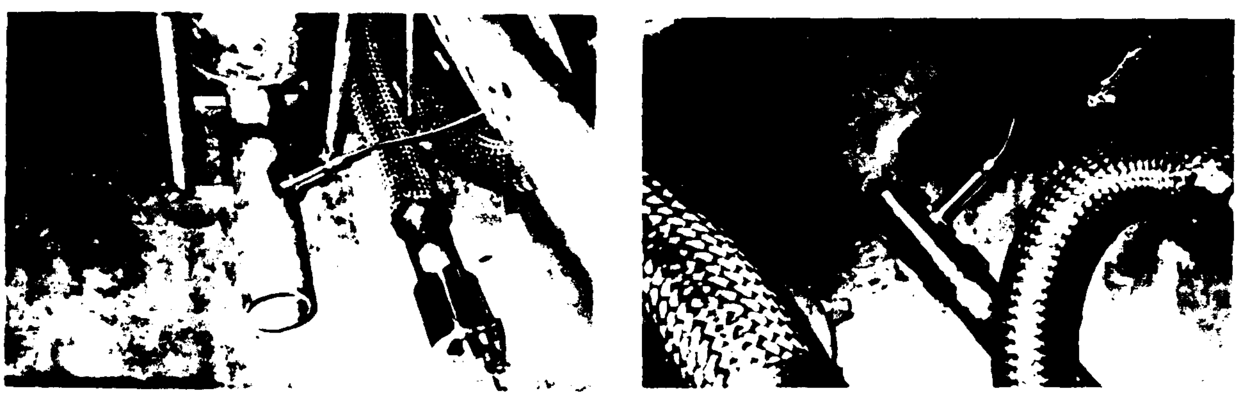


Figure 3-11. Test Tank Manhole Cover Equipment



Inlet Outlet

Figure 3-12. Enthalpy Meters Installed in the Pump Inlet/Outlet

detail in Section 3.2.3.8. A capacitance probe was used to measure LH_2/$TPLH_2$ level in the test tank, and resistance level sensors were used near the upgrade line to control the level in the tank during upgrade operations.

3.2.3.3.4 Submerged Pump

The variable speed submerged SH_2 pump installed in the test tank was a J. C. Carter Model 6100 liquid oxygen pump which was available to the program at no cost. This pump has a maximum volumetric flow of 0.05 m^3/sec (800 GPM) and a maximum head rise of 244 m (800 ft) of LH_2, equivalent to 172 kPa (25 psi). Clearly, the pump is much oversized for the STF application, however, by using a variable speed, variable frequency Sabina drive, the pump can be run at speeds as low as 6% flow (0.003 m^3/sec - 48 GPM). At these low speeds, the efficiency is very poor, as shown in Figure 3-13, but the input power is flat at about 6 kW (8 HP), resulting in substantial heat input to the SH_2.

MDA experienced recurring bearing problems with this pump, as described further in Section 4.1.3. Phenolic bearing retainers with extra wide webs (fewer balls) finally solved these problems.

3.2.3.3.5 Internal Piping

As shown previously in Figures 3-9 and 3-12, the outlet flow from the pump was split so that about half the flow was circulated within the tank to provide SH_2 mixing, and half the flow was expelled through the 2.5 cm (1-inch) pumped outflow (flex) line. This line could be valved closed using ROV-304 (see Figure 3-1) so that all of the pumped flow was circulated within the tank for SH_2 mixing. The enthalpy density meters at the pump inlet and mixing line outlet were used to assess the SH_2 solid fraction loss through the pump due to power losses. Additional piping into the tank included the 5 cm (2-inch) inflow/outflow line through the Simmonds capacitance gage, and the 5 cm (2-inch) upgrade line, previously shown in Figure 3-11.

3.2.3.4 Transfer Subsystem

3.2.3.4.1 Requirements

The transfer subsystem provides flow paths from the slush generator to the test tank to the triple point tank to the slush generator (see Figure 3-1). In addition, this subsystem contains an

The Variable Speed Submersible Pumping System Is Made Up of These Components

Motor

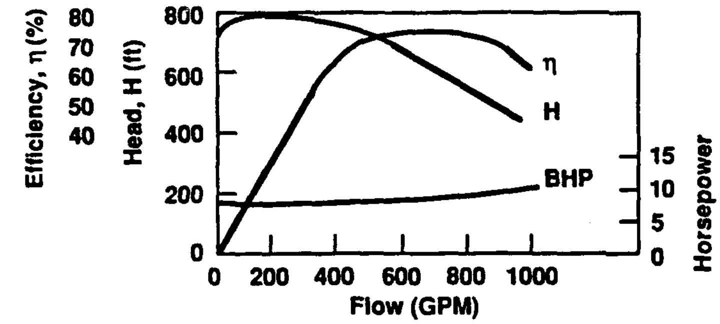
Mfr: U.S. Electrical
Frame: 8464
P/N: 403256
S/N: 1194723
Order No.: 13314
HP: 23
Volts: 200
Amps: 8
Freq: 400
Phase: 3
RPM:7300

Pump

Mfr: Carter
Model: 6100

Controller

Mfr: Sabina
HP: 20
Volts: 208 in, 0 to 200 out
Amps: 52
Freq: 60 in, 0 to 400 out



Calibration Curve for J.C. Carter 1096 Pump for LH_2 at 8300 RPM

FEATURES

- 800 GPM, 25 Psi Head
- Variable speed down to 6% flow
- Low NPSH, runs at 1.0 Psia with *30-in. tank head*

Figure 3-13. Submerged LH_2/SH_2 Pump Characteristics

instrument section which includes various temperature, pressure, flow, and density sensors, and a viewing section which contains transparent piping to video-view SH_2 flow phenomena. The transfer lines were required to be vacuum-jacketed and MLI-insulated to restrict the total heat leak to the SH_2. The vacuum jacketed lines required bayonet fittings to allow easy changeout and close-coupling to the tanks and valves. Vacuum jacketed flex lines were required near the test tank to allow the manhole cover to be removed. Two sizes of transfer line, 5 cm (2-inch) and 10 cm (4-inch) were originally planned, however, as discussed below, only the 5 cm line ended up being used.

3.2.3.4.2 Description

The transfer subsystem is shown in the foreground of Figure 5-1. The transparent section is to the right in Figure 5-1 and is shown in detail in Figure 3-14. The quartz tubing was sealed to the stainless steel line with Teflon seals and a V-band coupling. There were problems in sealing the

outer quartz tube (15.2 cm - 6-inch diameter) of the 5 cm size line. It was felt that sealing the 20.3 cm (8-inch) outer tube of the 10 cm size line would be time-consuming and unsuccessful, hence only the 5 cm size transfer line was installed and used.

In Figure 3-14, MLI is shown wrapped with 10 layers on the inner stainless steel line (to the left of the transparent tube). The MLI reduced the total heat leak into all of the transfer lines to about 7 watts. To the right of the transparent tubing, wrapped in plastic, is shown the instrument section, which included an enthalpy meter, a silicon diode, a pressure sensor, and an orifice and delta-P sensor for flow-rate measurement.

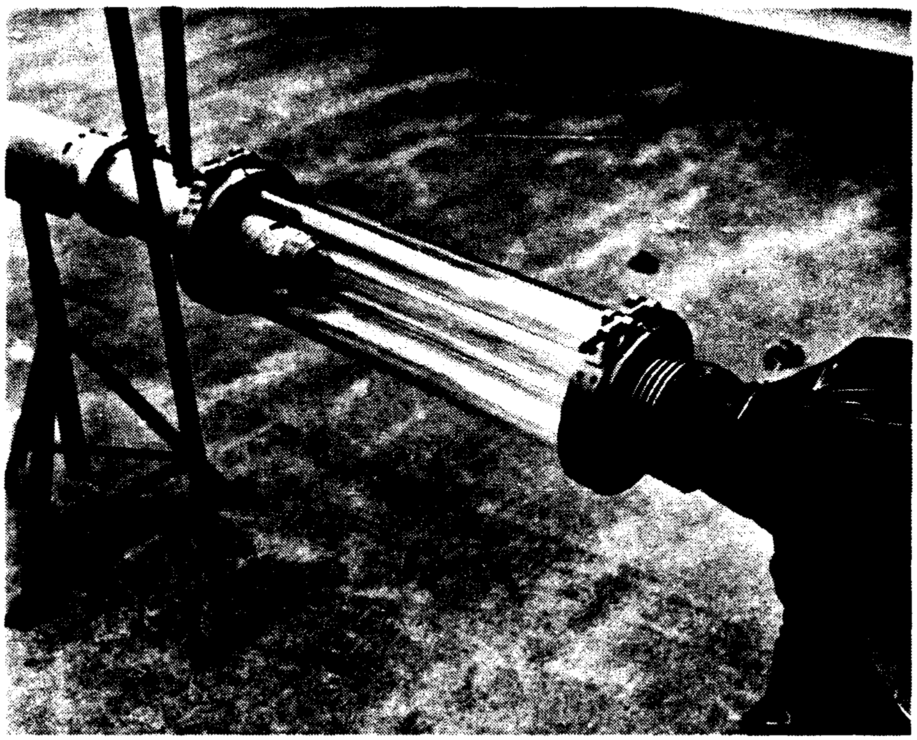


Figure 3-14. Transfer Subsystem Transparent Section Detail

The transfer subsystem vacuum jacket retained its vacuum throughout the program with only one pumpdown, and provided excellent thermal performance. Integral to the vacuum jacketed lines were relief valve/burst disc/check valve flowrater packages to provide venting of LH_2 trapped between valves. These same relief packages were used throughout the STF, as shown in Figure 3-1.

3.2.3.5 Triple Point Tank

3.2.3.5.1 Requirements

The triple point tank acts as a receiver for $TPLH_2$ from the test tank, and as a supply of $TPLH_2$ to the slush generator. The triple point tank had to be sized to accommodate the slush generator capacity during upgrade operations in the test tank, in which as much as 0.6 m^3 (150 gallons) of LH_2 may be in the test tank during loading tests. Hence the triple point tank was sized to 3.8 m^3 (1000-gallon) to assure that it could easily hold all of the fluids expected during testing. Because this tank had to contain $TPLH_2$, it was required to be vacuum jacketed and MLI insulated to minimize heat leak. Redundant heaters were specified to allow the tank to be quickly emptied and inerted. Both top and bottom fill and drain lines were specified, and the triple point tank, along with the test tank and slush generator, could be individually evacuated by the vacuum subsystem. The inner vessel was designed for 690 kPa (100 psig) to assure accommodation of the slush generator and test tank flow and pressure. A 10 cm (4-inch) access hole to contain temperature sensors and a capacitance probe was specified.

3.2.3.5.2 Description

The triple point tank is a horizontal, 3.8 m^3 (1000-gallon) vacuum jacketed, MLI insulated high performance LH_2/$TPLH_2$ storage tank. The predicted LH_2 loss from this tank is less than 1%/day (equivalent to about 15 watts). This tank is shown on the right of Figure 5-1. The tank had six silicon diodes spaced equally on a vertical rake suspended from the 10 cm (4-inch) access hole cover along with a capacitance probe to determine fluid depth and quantity. This tank performed very well throughout STF build-up, checkout, and test.

3.2.3.6 Pressurization Subsystem

3.2.3.6.1 Requirements

The pressurization system for the STF had many requirements:

- Provide GHe for slush generator pressurization and expulsion.
- Provide GHe and GH_2 at varied conditions for test tank loading and expulsion (pumped and pressurized) tests.
- Provide GH_2 for recirculation tests in the test tank.
- Provide GHe for actuation of certain (cold) valves and for purging of LH_2/SH_2/$TPLH_2$ plumbing.

The GHe was provided from high pressure tube trailers at a required flow rate of 0.031 kg/sec (4.14 lb/min). The GH_2 was also provided from high pressure tube trailers at a required flowrate of 0.043 kg/sec (5.73 lb/min). Both the GHe and GH_2 were required to be temperature-controlled to 20K, 80K and 300K. Since the tube trailer gas temperature was about 300K (or somewhat colder after expansion), heat exchangers were required to cool the pressurants to the desired temperature. Heat exchanger sizing calculations were performed to determine the feasibility of using a simple submerged coil instead of a complex heat exchanger for chilling the pressurant. The chilldown would be accomplished in two stages: LN_2 would pre-cool the gaseous pressurant to approximately 90K and LH_2 would cool it to 20K. Table 3-4 summarizes the results.

Table 3-4. Heat Exchanger Sizing

			LN_2				LH_2			
	Mass Flow		Coil I.d.		Length		Coil I.d.		Length	
Pressurant	(kg/sec)	(lb/min)	(cm)	(in)	(m)	(ft)	(cm)	(in)	(m)	(ft)
GHe	0.031	4.14	5.1	2.0	23.3	76.5	1.9	0.75	27.1	89.0
GH_2	0.043	5.73	5.1	2.0	120	394	2.5	1.0	49.7	163.0

Although Table 3-4 shows different heat exchanger requirements for GHe and GH_2, the more demanding requirements are for GH_2; hence the GH_2 heat exchanger requirements were used for both GHe and GH_2 conditioning.

3.2.3.6.2 Description

Pressurization system plumbing and components were sized at 2.5 cm (1-inch) diameter to provide the required flow rates. This system was insulated with 5 cm (2-inch) thick semi-annulus lengths of formed foam insulation taped as a vapor barrier. The sensible heat contained in the plumbing lines, valves, and insulation proved a barrier to chilling the pressurant as required.

The heat exchangers were existing units, shown on the right side of Figure 3-15. The large horizontal tank is the LH_2 heat exchanger, used to cool the pressurant to about 20K. The smaller vertical tank is the LN_2 heat exchanger, used to precool the pressurant to about 90K. Use of LN_2 as a precooler saved about 74% of the LH_2 cost which would have been necessary without the LN_2 heat exchanger. A temperature-controlled warm gas bypass line around the heat exchangers was to be used to control the pressurant temperatures to values intermediate to 20K and 300K. Instrumentation was used to measure the temperature, pressure, and delta-P across an orifice (hence flowrate) of pressurant entering the test tank or slush generator.

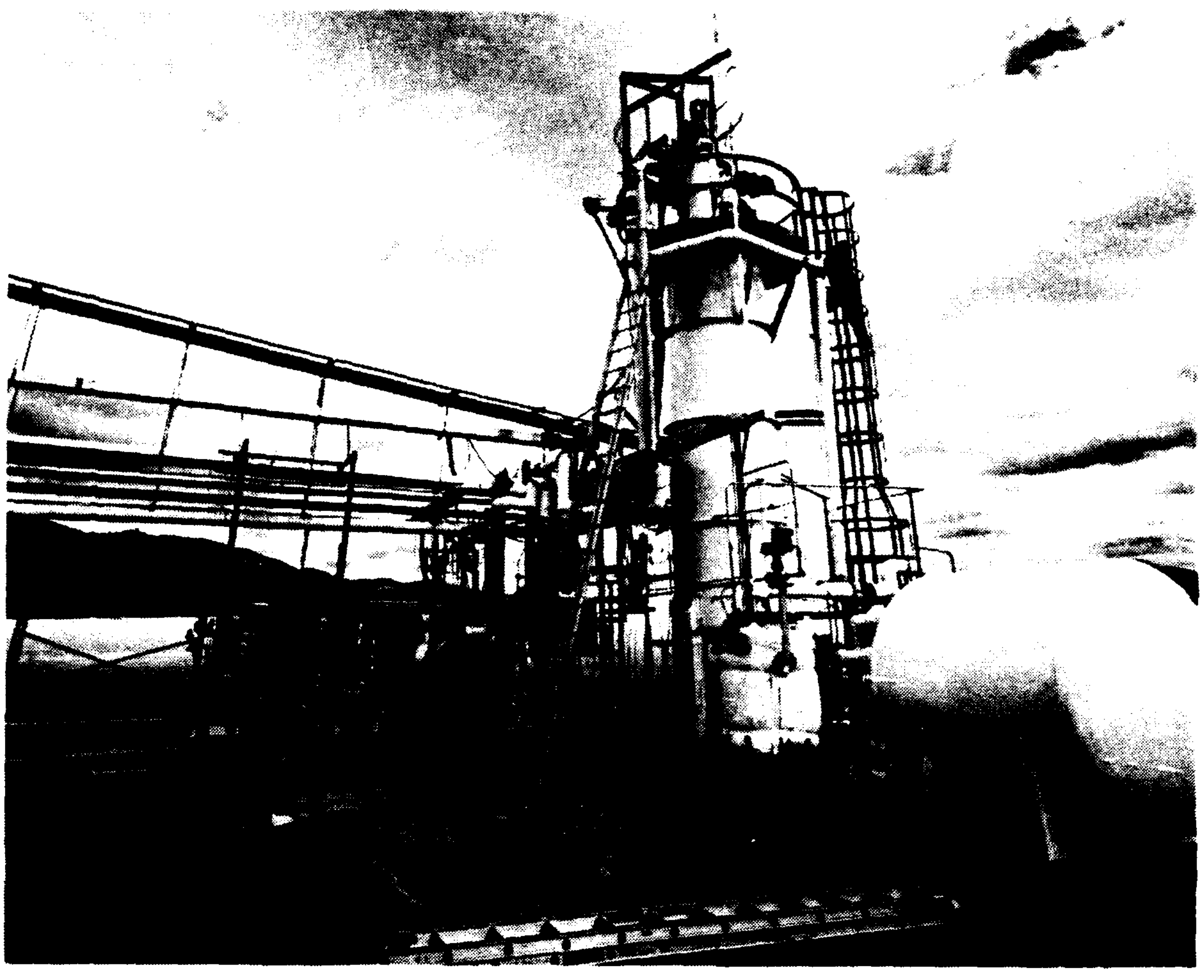


Figure 3-15. Pressurant Heat Exchangers and Slush Generator View

On the left side of Figure 3-15 is the control panel with shrouded video camera to monitor the flow of purge gas to various equipment. Many components were bagged and GHe purged to allow their operation in a hydrogen environment.

3.2.3.7 Sample Bottle

3.2.3.7.1 Requirements

The sample bottle was positioned next to the slush generator (as shown in the center of Figure 3-15) and was used to take samples of SH_2 during production and aging so that the SH_2 could be visually examined to determine SH_2 aging characteristics. The sample bottle had to provide good viewing visibility via a video camera, plus adequate thermal protection to preserve the SH_2 for viewing. The sample bottle also had to have the capability of being chilled down and evacuated to allow the sampling process to take place.

3.2.3.7.2 Description

The sample bottle was a 0.076 m^3 (20 gallon) glass Dewar with vacuum jacket which was identical in configuration to the glass Dewar used in the subscale test facility (flask 2 in Figure 4-18). A vertical narrow glass window was installed in the vacuum jacket to allow video viewing of the contents which were lighted through the Dewar lid. Visibility into the sample bottle was excellent. Inside the sample bottle was an instrument rake which included silicon diodes, and an overflow glass jar with a 20-mesh screen attached to provide a size reference for the measurement of SH_2 particles. An NRA densimeter was also used on the sample bottle to provide SH_2 density (solid fraction) measurements. As shown previously in Figure 3-1, the sample bottle could be evacuated by the vacuum subsystem, and chilled down with LH_2 prior to sampling of SH_2. The sample bottle was drained by allowing the SH_2/LH_2 to boil away, which occurred in several minutes due to the lighting heat input and the heat leak through the viewing window.

3.2.3.8 Instrumentation and Control

3.2.3.8.1 Requirements

The STF was heavily instrumented to provide data to understand and correlate the phenomena associated with SH_2 technology testing. Each major element of the STF had a complement of instruments to measure pressure, temperature, flow, density and other data as previously described above for each subsystem.

Control of the STF functions was performed from a barricaded remote blockhouse for safety reasons. All of the valves and regulators needed for operation of the STF were remotely operated; the larger valves were pneumatically actuated with GHe using solenoid actuated pilots. The slush generator vacuum valve and mixer were automatically and remotely operated from the blockhouse as described previously in Section 3.2.3.1.

3.2.3.8.2 Description

A complete listing of all the STF instrumentation is shown in Table 3-5. Data are taken with an HP-3000 computer at up to one scan per second. Silicon diodes were used for temperature sensors because of their relatively low cost and high accuracy at SH_2 temperatures. In general, rakes of silicon diodes agreed within less than 0.1K. Capacitance pressure sensors capable of being submerged in LH_2/SH_2 were generally used and offered high accuracy. Existing non-submersible strain gage type pressure transducers were used in ambient temperature applications (pressurant, purge gas, etc.).

Table 3-5. Slush Hydrogen Test Facility Instrumentation

FUNCTION	DESCRIPTION	TYPE	RANGE	ACCURACY
Slush Generator				
DT-205	Density	NRA	4-5.2 lb/ft^3	1%
PT-211	Pressure	Cap.	0-2 psia	0.25%
LT-206	Level, liquid	Capacitance	24-192 in LH_2	0.5%
LT-217	Level, liquid	Delta-P	0-14 in H_2Od	
PT-225	Pressure (PS)	Cap.	0-50 psia	0.25%
RPM-201	Speed, stir motor	Pot	0-100%	
TD-201 to	Temp., tank rake	Si Diode	4-300 K	0.5 K
TD-228	Temp., tank rake	Si Diode	4-300 K	0.5 K
500 Gallon Test Tank				
TR-301	Temp., tank rake	GRT	4-300 K	0.2 K
PT-301	Press., ullage	Cap.	0-50 psia	0.25%
PT-302	Press., prop outlet	Statham	0-50 psia	0.25%
LT-301	Level	Delta-P	0-6 in H_2Od	
DP-301	Pump flow (DP)	Cap.	0-5 psia	0.25%
DT-301	Density	Enthalpy	4-5.2 lb/ft^3	
DI-301	Current, enthalpy	Resistor		
LT-302	Level, liquid	Capacitance	0-42 in LH_2	0.5%
DT-302	Density	Cap.	4-5.2 lb/ft^3	
IT-302	Power, heater			
TD-301 to	Temp.,liquid/ullage	Si Diode	4-300 K	0.5 K
TD-324	Temp.,liquid/ullage	Si Diode	4-300 K	0.5 K
HTR-301	Heater temp.	T/C,E	70-300 K	3 K
DT-303	Density	Enthalpy	4-5.2 lb/ft^3	
DI-303	Current, enthalpy	Resistor		
DT-304	Density	NRA	4-5.2 lb/ft^3	1%
TD-325 to	Wall temp.	Si Diode	4-300 K	0.5 K
TD-342	Wall temp.	Si Diode	4-300 K	0.5 K
FT-303	Press. flow	Delta-P	0-150 psia	0.5 psia
RP-301	Motor speed	Tach.	0-100%	
TD-343 to	Temp., press.manifold	Si Diode	4-300 K	0.5 K
TD-345	Temp., press.manifold	Si Diode	4-300 K	0.5 K
Triple Point Tank				
TD-501 to	Temp., tank rake	Si Diode	4-300 K	0.5 K
TD-506	Temp., tank rake	Si Diode	4-300 K	0.5 K
PT-551	Pressure	Cap.	0-50 psia	0.5%
LT-501	Level, liquid	Delta P	0-6 in H_2Od	
Sample Bottle				
TD-131 to	Temp., rake	Si Diode	4-300 K	0.5 K
TD-136	Temp., rake	Si Diode	4-300 K	0.5 K
PT-151	Pressure	Cap.	0-50 psia	0.25%
DT-151	Density	NRA	4-5.2 lb/ft^3	1%
Transfer Subsystem				
TD-470	Temp., transfer inlet	Si Diode	4-300 K	0.5 K
TD-471	Temp., transfer outlet	Si Diode	4-300 K	0.5 K
TD-472	Temp., flowmeter	Si Diode	4-300 K	0.5 K
PT-470	Press., transfer inlet	Cap.	0-50 psia	0.25%
DP-472	Flow (DP)	DP10	0-5 psid	0.5%
PT-472	Press. flow	Cap.	0-50 psia	0.25%
DT-401	Density	Enthalpy	4-5.2 lb/ft^3	
DI-401	Current, enthalpy	Resistor		
TD-661	Temp., SG outlet	Si Diode	4-300 K	0.5 K
Pressurization Subsystem				
FT-909	Flow, to SG	Delta P	0-10 psid	
LT-936	Level, LN_2 HX	Delta P	0-36 in H_2Od	0.25%
LT-936-02	Level, LH_2 HX	Delta P	0-6 in H_2Od	0.25%
TE-969	Temp., gas	T/C, E	70-300 K	3 K
PT-932	Press., HX exit	Cap.	0-150 psia	0.25%
TD-932	Temp., LH_2 HX outlet	Si Diode	4-300 K	0.5 K
TE-934	Temp., LH_2 HX vent	T/C, E	70-300 K	3 K
TE-918	Temp., LN_2 HX outlet	T/C, E	70-300 K	3 K
TE-913	Temp., LN_2 HX vent	T/C, E	70-300 K	3 K
TD-935	Temp., TT press. gas	Si Diode	4-300 K	0.5 K
PS-901	Press., purge gas	P Switch	10 psig	

Capacitance probes were used for level sensing of $LH_2/TPLH_2$ in the slush generator and test tank. These probes can not effectively be used with SH_2 for two reasons. First, it is difficult to obtain a representative sample of SH_2 within the confines of the capacitance probe, which is annular-tubular; an open capacitance plate pair would be preferred. Second, the capacitance reading yields an indeterminate level sensing when vapor, liquid, and solid coexist at the triple point.

Enthalpy gages, developed under MDA IRAD, were used to determine SH_2 solid fraction (density) for flowing SH_2. This gage works on the principle that the enthalpy of SH_2 varies significantly with solid fraction, and convective heat transfer is proportional to the enthalpy difference. The gage is implemented by using a heated calorimeter exposed to the SH_2 flow. The gage determines the power required to maintain a 2K temperature difference between the flowing SH_2 and the calorimeter. This power is converted to an enthalpy (solid fraction). These units were tested and validated during the pre-STF tests and worked adequately during the STF testing.

Nuclear radiation attenuation (NRA) densimeters were used extensively in the STF. These devices beamed gamma rays through the tank and fluid to a detector on the other side of the tank. Attenuation of the beam by the tank and fluid was converted to an effective density of the SH_2 (the tank density contribution was calibrated out). These densimeters were calibrated at $NBPLH_2$ and $TPLH_2$ conditions and gave SH_2 density accuracies of about 1%. The NRA densimeters were the primary measurement device for determining slush generator production and aging performance as well as test tank loading and upgrading performance. The NRA data were correlated with SH_2 melt-back tests during the follow-on STF test program and were found to be accurate; however these gages tended to drift and required recalibration relatively frequently. Another issue is that the NRA gages only give density data for the SH_2 in the beam -- spatial distribution of SH_2 density can not be directly measured but can be inferred during outflow past the NRA gage.

All of the STF control and data recording were performed from a barricaded, remote blockhouse. The blockhouse interior is shown in Figure 3-16. In addition to the data and control panels in the center of the figure, there were a number of video monitors (shown at the left in the figure). There were a total of six video cameras which were monitored during STF testing: 1) slush generator interior, 2) test tank interior, 3) sample bottle, 4) transfer subsystem transparent section, 5) purge gas control panel, and 6) overall STF view for safety monitoring. In addition, the three NRA readouts were out of the figure to the right. A large number of critical parameters such as tank pressures, temperatures, density, etc., were continuously available for display in a series of menus displayed next to the principal control panel which showed the open/closed status of all valves, as well as other control elements.

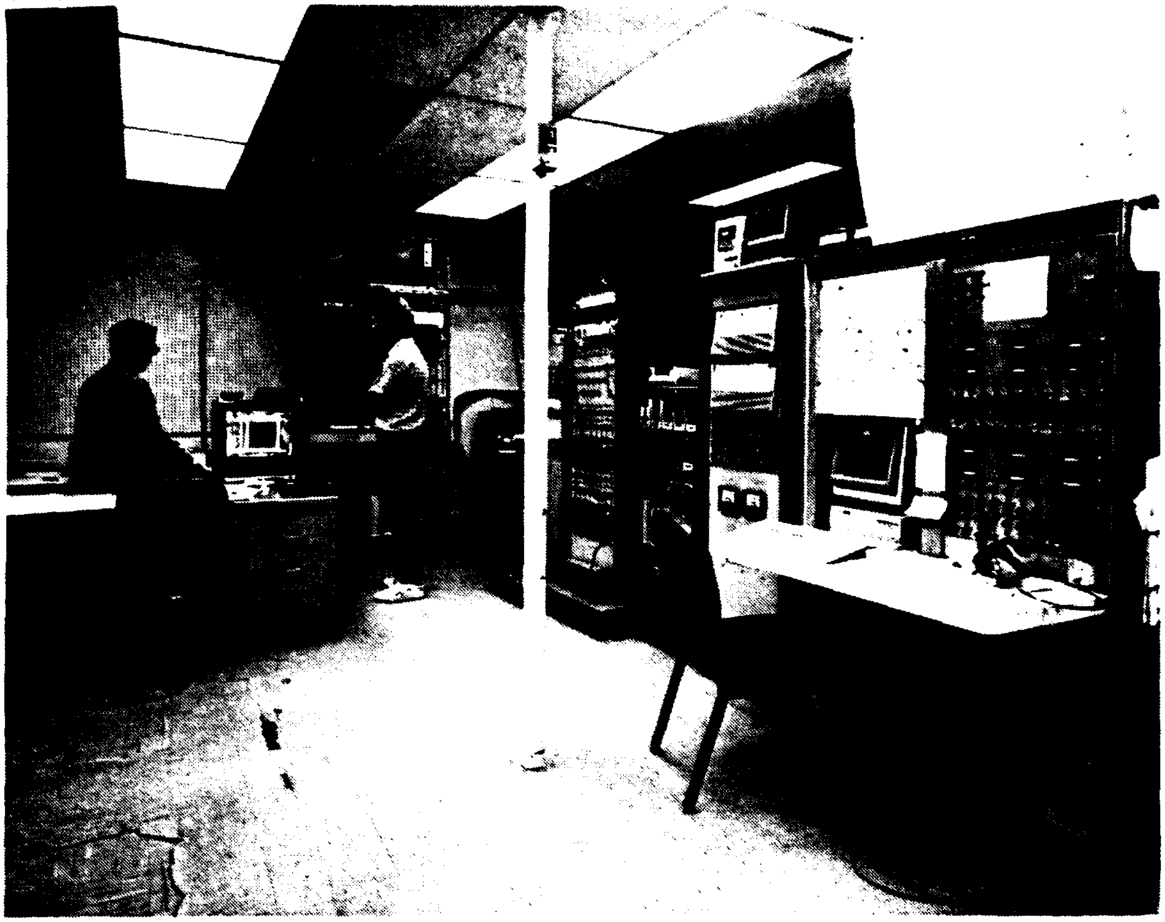


Figure 3-16. Interior View of the STF Blockhouse

Due tothe confined blockhouse space, the number of personnel present during testing was restricted to about 7-8 people. Testing could be efficiently run with only 4-5 people, since many of the SH_2 operations were semi-automated (such as SH_2 production and aging).

3.2.3.9 Mechanical and Electrical Design

The design of the STF included a complete set of drawings used to fabricate the STF, as shown in Table 3-6. In addition, sketch engineering was used where appropriate for brackets and minor details. Once these drawings were released, red lines of the drawing were used for changes and formal changes were not released. Rather, a complete set of red-lined drawings was delivered to NASA-LeRC at the completion of the STF fabrication.

Table 3-6. STF Drawings

System Schematic	EPL6303031
Facility Layout	EPL6303058
AP/TT Transfer Line	EPL6303062
Transfer Subsystem	EPL6303062
Fill and Return Plumbing	EPL6303062
Triple Point Tank	EPL6303090
Vacuum Subsystem	EPL6303096
Pressurization Subsystem	EPL6303099
Test Tank Flange	EPL6303136
Subscale Generator	EPL6302905
Subscale Support Structure	EPL6302905
Sample Dewar	EPL6303133
Instrumentation/Control	EPL6303070
Subscale I/C	EPL6303071
Slush Generator I/C	EPL6303072
Transfer I/C	EPL6303073
Test Tank I/C	EPL6303074
Triple Point I/C	EPL6303075

3.3 Safety and Coordination

3.3.1 Safety Issues and Requirements

The principal safety issues arising from use of SH_2 are: 1) low cryogenic temperatures, 2) hydrogen flammability, and 3) the low vapor pressure (52.8 torr) of SH_2 which, being a vacuum, can lead to air in-leakage into the SH_2 with resulting potential SH_2/air deflagration/ detonation. As described previously, the design requirements for all subsystems and components included leak tightness and/or purging to insure that air in-leakage could not occur.

The requirement for explosion proofing of electrical equipment complied with NFPA/NEC-Class 1, Division 2, Group 8 for a hydrogen environment. The acceptable alternative was to remove the hazard by placing the electrical device in a gaseous nitrogen (GN_2) purged enclosure. This option was considered for existing hardware which does not meet the above NEC requirement. The requirement for purging complied with NFPA-496 for type Z purging.

In addition, the STF design requirements included IR video surveillance, remote location, water deluge, and grounding of all hydrogen vessels and plumbing.

3.3.2 Safety Design

As a consequence of the low cryogenic temperatures of SH_2, heat leak into and boiling of the SH_2 will occur. Therefore vacuum jacketing and insulation was used on all SH_2 vessels and plumbing to minimize heat leak, and pressure relief valves/burst disc packages were used whenever valves could trap SH_2 or LH_2 in lines (see Figure 3-1).

The entire STF was carefully sealed and checked for leakage using GHe and a mass spectrometer (sniffer) to assure leak tightness. In addition, provisions for sampling of the major vessels (slush generator, test tank, and sample bottle) using a vacuum-pumped oxygen detector system was designed into the STF. The oxygen detector was borrowed from NASA-LeRC, and checked out, but never detected air in-leakage. However, detecting and dealing with air in-leakage was a constant concern. Special procedures for sampling for air leakage and handling air contamination of the SH_2 were prepared.

During the subsequent SH_2 testing, a vacuum pump failure during SH_2 production allowed purge GN_2 to enter the slush generator where it froze into very fine crystals which settled into the SH_2. Since it was unclear whether air had also entered with the GN_2, the entire SH_2 load was disposed of. This was accomplished by purging the slush generator with warm (ambient temperature) GHe until the SH_2 had melted, boiled off, and been purged from the slush generator.

The sample bottle was to be used to sample the slush gènerator contents to determine SH_2 quality (solid fraction) and to sample for air (oxygen) in the SH_2. This was accomplished, but oxygen was not detected.

To handle the H_2 flammability issue, all potentially hazardous electrical equipment (e.g. motors) were placed in GN_2-purged enclosures. Surveillance of the STF with an IR video camera was done during testing. During the first few tests, until the integrity of the STF was verified, strings of cheesecloth, used as fire detectors, were placed near potential leakage points, such as flanges, valves, etc. When STF operation became more routine, the cheesecloth strings were removed and the IR camera was relied on.

A large water deluge system was installed in the STF, with spray nozzles directed at critical areas of the STF, such as the slush generator, test tank, vent stack, sample bottle, and transparent section. The deluge system was tested but never used during SH_2 testing.

A comprehensive equipment grounding system was installed at the STF, which included all major vessels, the vent stack, and the plumbing. It was required that the resistance to ground be less than 10 ohms, and this requirement was included in the startup and testing procedures.

3.3.3 Safety Reviews

A number of safety reviews and hazards analysis meetings were held during the course of the contract. A Design and Safety Hazards Review meeting with MDA and MMAG was held on

4-5 August 1988 at Air Products (APCI) headquarters in Allentown, Pennsylvania. Agenda items included a project status review from both MDA and APCI Program Managers; design reviews of the slush generator, viewing windows and mixer assemblies; a detailed discussion of scope split; and operational/safety review. These discussions resolved all major scope issues and clarified the operating and safety philosophies.

All participants generally agreed on the safety philosophy for the STF, with the primary concern of personnel protection. MMAG's approach was to include hardware into the design to assure safe operation. As the STF was a test facility and not an operating plant, the operation and access will be carefully controlled by procedure. MMAG and APCI collectively assembled an FMEA in advance of the 4 November 1988 Design Review. This assured an agreed approach to safety, with all critical hardware identified.

A safety meeting was held at MMAG on 21 February 1989. General discussion from that meeting addressed the various major safety concerns with may be encountered during production. Specific actions from the meeting included:

- MDA established who was responsible for erecting the slush generator.
- MMAG assessed the need for a liquid dump line leading into the stack or pond.
- MMAG looked at the response to sudden pressure rise in the generator.
- APCI provided a dimensioned instrumentation drawing.
- MMAG provided a complete instrumentation drawing with dimensions.
- MMAG assembled the alarm sheet.
- MMAG provided line distance between the control room and slush generator.
- MMAG provided pressure regulation and separate flow measurement for the test tank with concurrent plumbing of the GHe supply and GH_2 supply.

In July 1989, Air Products hosted a review meeting for the Slush Hydrogen Safety Study which was attended by MDA and MMAG representatives. The presentation included an overall status update on the study as well as the draft of the addendum to the existing safety report.

The various safety reviews described above were instrumental in identifying and resolving the various safety issues relevant to the design and operation of the STF. In addition, numerous technical coordination meetings were also held throughout the program. In many of these meetings design and safety issues were discussed. These meetings are described below.

3.3.4 Technical Coordination Reviews

An STF status review was completed on 21-22 December 1988. The program schedule and checkout plan were presented along with an overview of the Task II test plan. The overall STF design was approved, however, it was agreed that a 0.076 m^3 (20 gallon) sample Dewar would be incorporated into the facility.

The checkout test plan for the STF was completed and submitted for customer approval. Data was prepared in support of the 18-19 January 1989 quarterly review at NASA-LeRC in Cleveland, Ohio. Testing material prepared for presentation included a synopsis of subscale Part 1 testing, data reduction and evaluation charts, and conclusions and recommendations.

A general status meeting on the STF was held on 20 February 1989. The following items were discussed:

- NASA-LeRC requested additional temperature instrumentation in the test tank.
- MDA looked into obtaining a feed through connector.
- NASA-LeRC required a review of the pressurization technique during the loading and upgrading tests.
- MMAG looked at possibly adding a self-relieving regulator to control the pressure.
- Status of the capacitance meter from Simmonds planned for subscale testing was requested.
- A request was made to provide an instrumentation schematic to show instrumentation locations with dimensions.

An additional STF design status meeting was held at MMAG on 29 March 1989 to discuss resolution of the above design details.

The STF test plan was completed and submitted to NASA-LeRC in February 1989. Categories of tests include production, aging, pressurized expulsion and transfer, pumped expulsion and transfer, loading and upgrading, and warm GH_2 recirculation. Upon review of the test plan in April 1989, NASA-LeRC requested the following additions be incorporated into the STF design:

- Add diodes to the test tank wall to provide heat transfer data for analysis of the thermal performance of the test tank.
- Add the capability for proportional control of the pressurant into the test tank during the loading and upgrading tests. Also provide a means for the pressurant flow to be measured during transfer.
- Add a sheet to the schematic showing the locations of the instrumentation inside each vessel.

Finally, a pre-test Readiness Review was held at MMAG on 21 September 1989, to review the assembly status and checkout of the STF. The final assembly of the STF major components was completed and the checkout of the system was initiated in September 1989. The checkout of the system included:

- Vacuum system proof and leak
- Pressurization system leak check
- Transfer system leak check
- Vacuum decay on the slush generator, test tank and triple point tank
- Proof test of the test tank
- System functional verification
- Control and data acquisition system checkout
- System drying with hot gas
- Mixer operation
- Vacuum system operation

The system checkout continued into October 1989 with the LN_2 cold shock of the slush generator and the production and transfer of nitrogen slush, as described below in Section 4.4.

4.0 TASK II - TECHNOLOGY TESTING USING SH_2

4.1 Pre-STF Testing at Wyle Labs, Norco, California

The $1.9 m^3$ (500-gallon) test tank, shown installed at Wyle Labs, Norco, California in Figure 4-1, was used to simulate the NASP vehicle tank, and was used for pressurization and pumping tests prior to its installation at the STF. In these early tests, SH_2 was produced in the test tank using a water-sealed vacuum system (see Figure 4-1). This early system had insufficient capacity to provide nominal high density SH_2, the maximum SH_2 fraction produced was about 20%, and aging to higher SH_2 fractions was not practical because of the relatively high heat leak to the tank (~300 watts). However, the SH_2 was adequate for early exploratory tests on SH_2 and triple point liquid hydrogen ($TPLH_2$) pressurization and expulsion.

As a minimum, the initial testing was to address the following objectives:

- SH_2 tank pressurization requirements
  - — steady state
  - — expulsion
- Pressurization effects of simulated sloshing
- Pressurant diffuser design requirements
- Pressurization effects of simulated recirculation
- Characterize mixing/transfer pump for
  - —NPB LH_2
  - — $TPLH_2$
  - — SH_2
- Evaluate mixing, nozzle design, and orientation
- Determine pump power consumption for uniform mixing

In order to facilitate the parallel performance of Task I and early Task II testing, the test plans for the early Task II testing (MDA and MMAG) were submitted and approved by NASA-LeRC at the program kickoff meeting.

The vacuum, pressurization, and flow systems for these early tests are shown schematically in Figure 4-2. Both gaseous helium (GHe) and gaseous hydrogen (GH_2) were used as pressurants. The GHe was cooled to about 80K in a heat exchanger with normal boiling point liquid hydrogen ($NBPLH_2$) to simulate ground prepressurization of the NASP fuel tank. The GH_2 was used unconditioned, and was at about 300K as sensed by a thermocouple on the pressurization line. The test tank was instrumented with 23 temperature sensors separated vertically by 0.025 m (one inch) in the ullage, and by 0.15 m (six inches) in the liquid. During these early tests, there were no wall temperature sensors; eighteen wall temperature sensors were added for the future STF

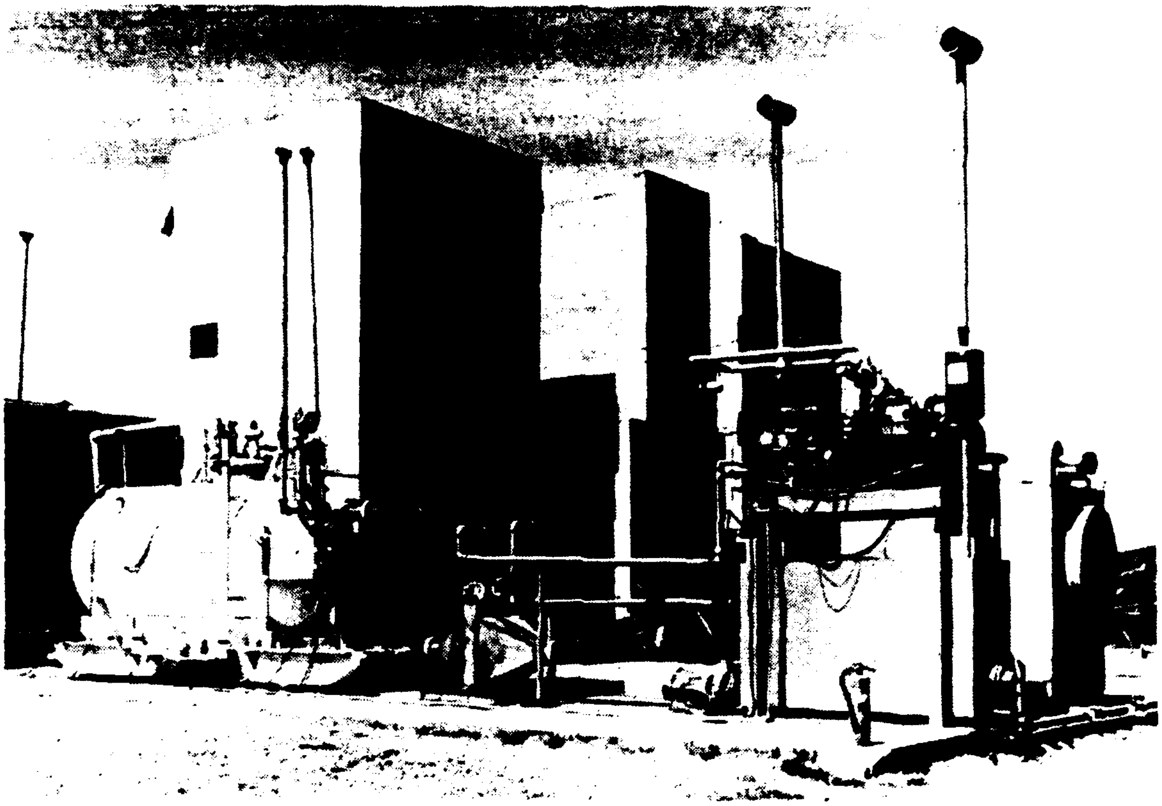


Figure 4-1. MDA 1.9 m^3 (500-Gallon) Slush Hydrogen Test Tank

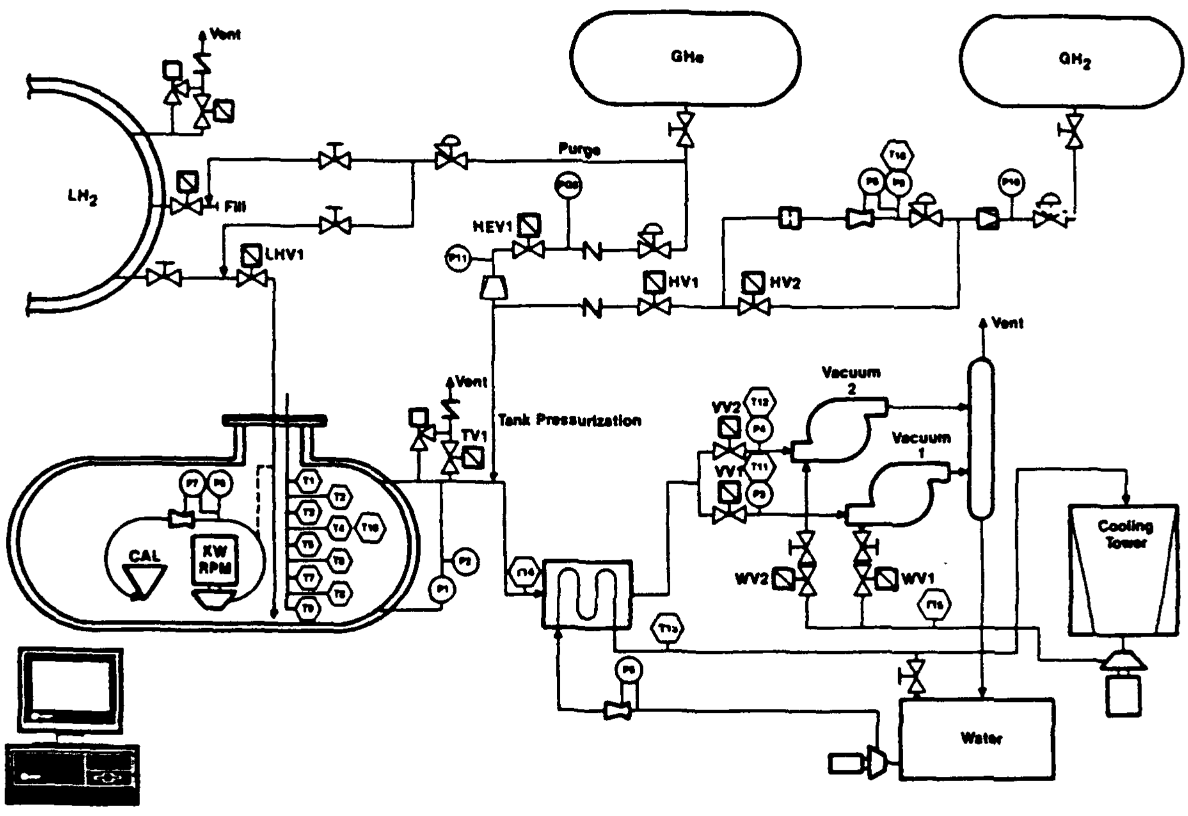


Figure 4-2. MDA Slush Hydrogen Test Facility Schematic

pressurization tests. Tank pressure and pressurant flow rate and condition data were also taken.

4.1.1 Pressurization Test Results

The pressurization test matrix for the pre-STF tests is shown in Table 4-1. The matrix varies slush fraction, pressurant and tank pressure. The pressurants were GHe at about 80K (cooled in a $NBPLH_2$ heat exchanger) and GH_2 at about 300K. The test procedure was to prepressurize the test tank to the first pressure level [e.g., 110 kPa (16 psia)], hold, and then expel a small portion of the tank contents. Expulsion was then stopped, and the tank vacuum-pumped back down to 6.9 kPa (1.0 psia) and additional SH_2 produced (if a SH_2 run). The tank was then pressurized to the second pressure level [e.g., 148 kPa (21 psia)], held, and then another small portion of the tank contents was expelled. Expulsion was stopped, and the tank was again vacuum-pumped down to 6.9 kPa (1.0 psia) (and more SH_2 produced, as applicable). The tank was then pressurized to the third pressure level [e.g., 179 kPa (26 psia)], held, and then the remaining tank

Table 4-1. Pre-STF Test Matrix

Run No.	Solid Fraction	Pressurant	Tank Pressure kPa	Tank Pressure psia	Comments
2.0-1	0	GHe	110	16	
2.0-2	0	GHe	148	21	
2.0-3	0	GHe	179	26	Empty Tank
2.0-4	0	GH_2	110	16	
2.0-5	0	GH_2	148	21	
2.0-6	0	GH_2	179	26	Empty Tank
2.0-7	0	GHe/GH_2	110/148	16/21	
2.0-8	0	GHe/GH_2	110/179	16/26	Empty Tank
2.0-9	25	GHe	110	16	
2.0-10	25	GHe	148	21	
2.0-11	25	GHe	179	26	Empty Tank
2.0-12	50	GHe	110	16	
2.0-13	50	GHe	148	21	
2.0-14	50	GHe	179	26	Empty Tank
2.0-15	25	GH_2	110	16	
2.0-16	25	GH_2	148	21	
2.0-17	25	GH_2	179	26	Empty Tank
2.0-18	50	GH_2	110	16	
2.0-19	50	GH_2	148	21	
2.0-20	50	GH_2	179	26	Empty Tank
2.0-21	25	GHe/GH_2	110/148	16/21	
2.0-22	25	GHe/GH_2	110/179	16/26	Empty Tank
2.0-23	50	GHe/GH_2	110/148	16/21	
2.0-24	50	GHe/GH_2	110/179	16/26	Empty Tank

contents were expelled at constant pressure. The same pressurant was used for prepressurization and expulsion, except for tests 2.0-7 and 2.0-8. In these tests, GHe was used for prepressurization to 110 kPa (16 psia), then GH_2 was used for pressurization to and expulsion at either 148 kPa (21 psia) (2.0-7) or 179 kPa (26 psia) (2.0-8). It is estimated that the actual SH_2 fraction for the SH_2 tests was 16-20%. Much higher SH_2 fractions would be tested in the planned STF tests. Only the shaded tests shown in Table 4-1 were completed before the GH_2/water heat exchanger in the vacuum pumping system failed, terminating further tests.

The pressure-time trace for test 2.0-3 using (cold) GHe pressurant with $TPLH_2$ is shown in Figure 4-3, and with SH_2 (Test 2.0-11) in Figure 4-4. The dashed line in the figures indicates the initiation of outflow. There are two phenomena of note: 1) there is very little pressure collapse at the initiation of outflow (dashed line in the figures) with GHe pressurant, and 2) it takes twice as long to pressurize SH_2 as $TPLH_2$ (430 sec versus 200 sec). This disparity in times is believed due to chilling of the cold, heavy GHe at the interface by the melting SH_2 . With $TPLH_2$, the interface layer would warm up, reducing the heat flow from the GHe, and allowing more rapid pressurization.

Very different ullage pressure behavior occurs with (warm) GH_2 pressurant, as shown in Figure 4-5 for test 2.0-6. Pressurization of $TPLH_2$ with GH_2 is nearly the same as with GHe (~240 to 200 sec). But with SH_2, GH_2 pressurization is even quicker (~150 sec) as shown in Figure 4-6 for test 2.0-17, and much quicker than with GHe (~430 sec). This is thought to be due to the fact that the GH_2 can maintain a very steep temperature gradient in the ullage at the interface as its thermal conductivity is about half that of GHe; hence there is much less GH_2 cooling and pressurant requirement. The most striking behavior in Figure 4-5 is the significant ullage pressure collapse following initiation of outflow. This is believed due to GH_2 condensation at the interface, aided by the surging of the outflow in the warm transfer line. Although the pressurant is full on from the start of outflow, it is unable to keep up with the collapse until ~600 sec. The same kind of collapse also occurred with GH_2 pressurization of SH_2. It is believed that outflow line surging ceased and actual outflow began at ~625 sec.

In general, for the tests at 179 kPa (26 psia) the initial $TPLH_2$ or SH_2 level was at about 0.5 m (20 inches) resulting from the initial fill level combined with pumping to obtain SH_2 and the limited previous outflows. The raw data for all tests were published in a NASP special report (Reference 1).

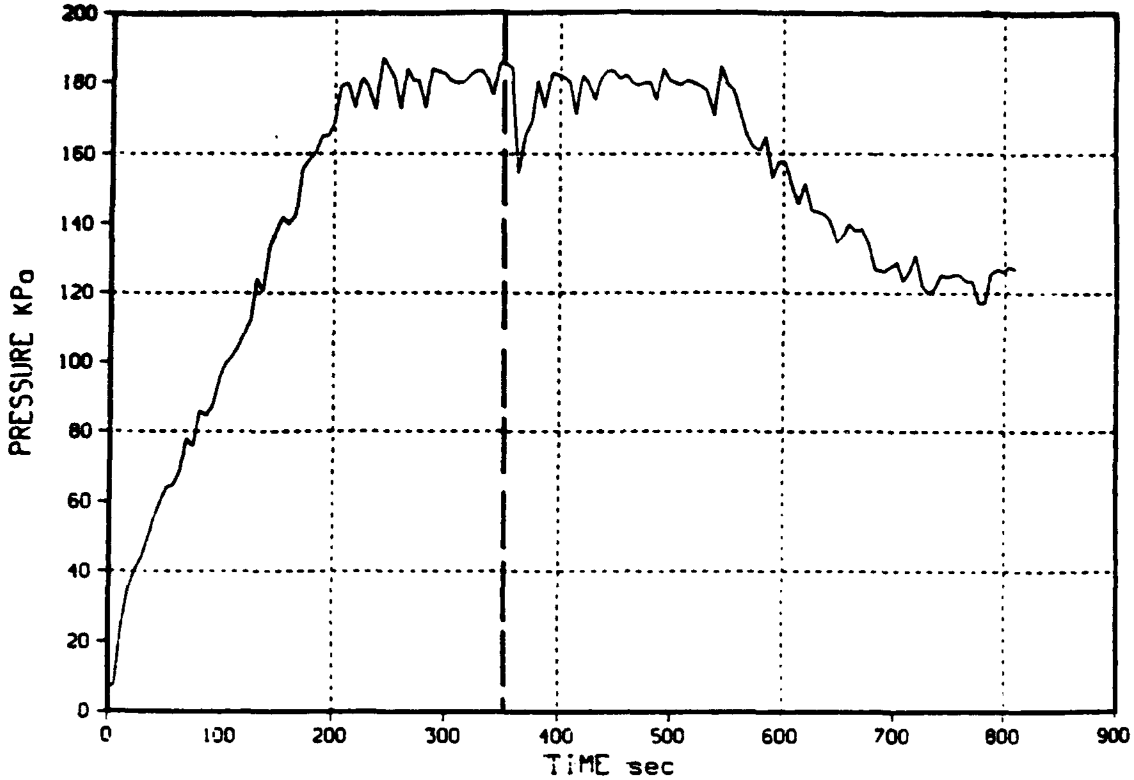


Figure 4-3. Pressure Profile for Test 2.0-3; GHe Pressurization of $TPLH_2$

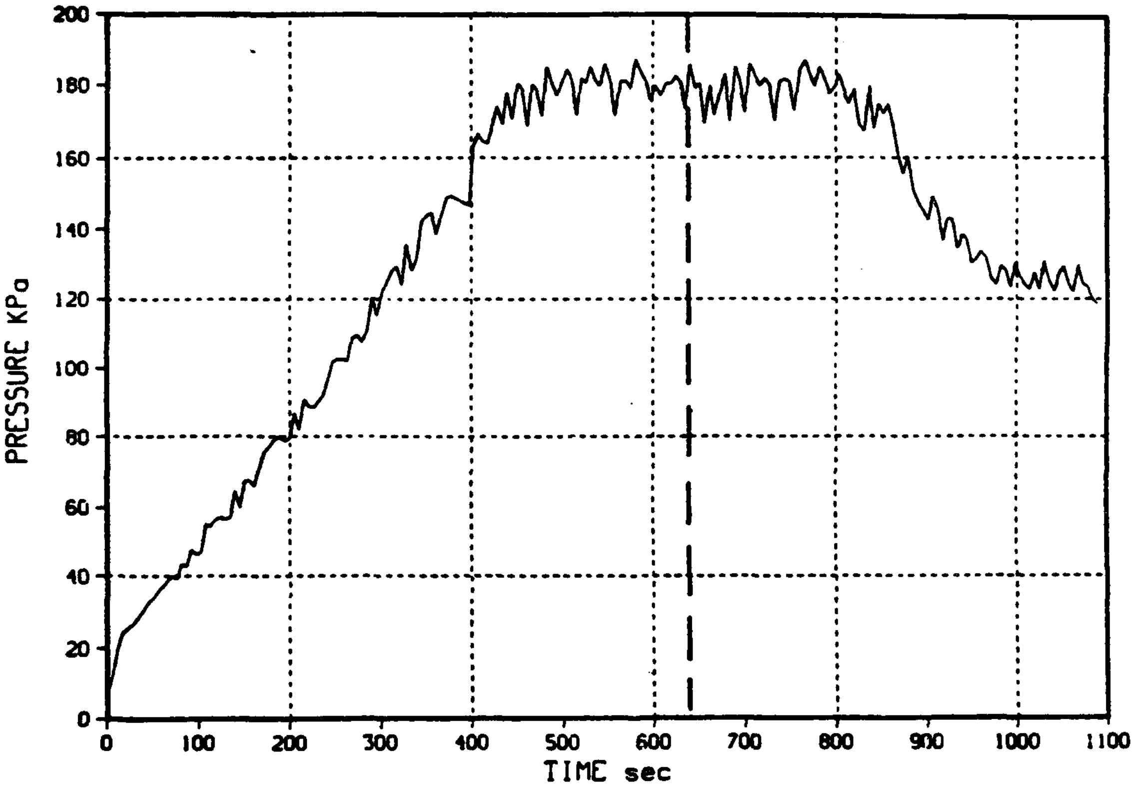


Figure 4-4. Pressure Profile for Test 2.0-11; GHe Pressurization of SH_2

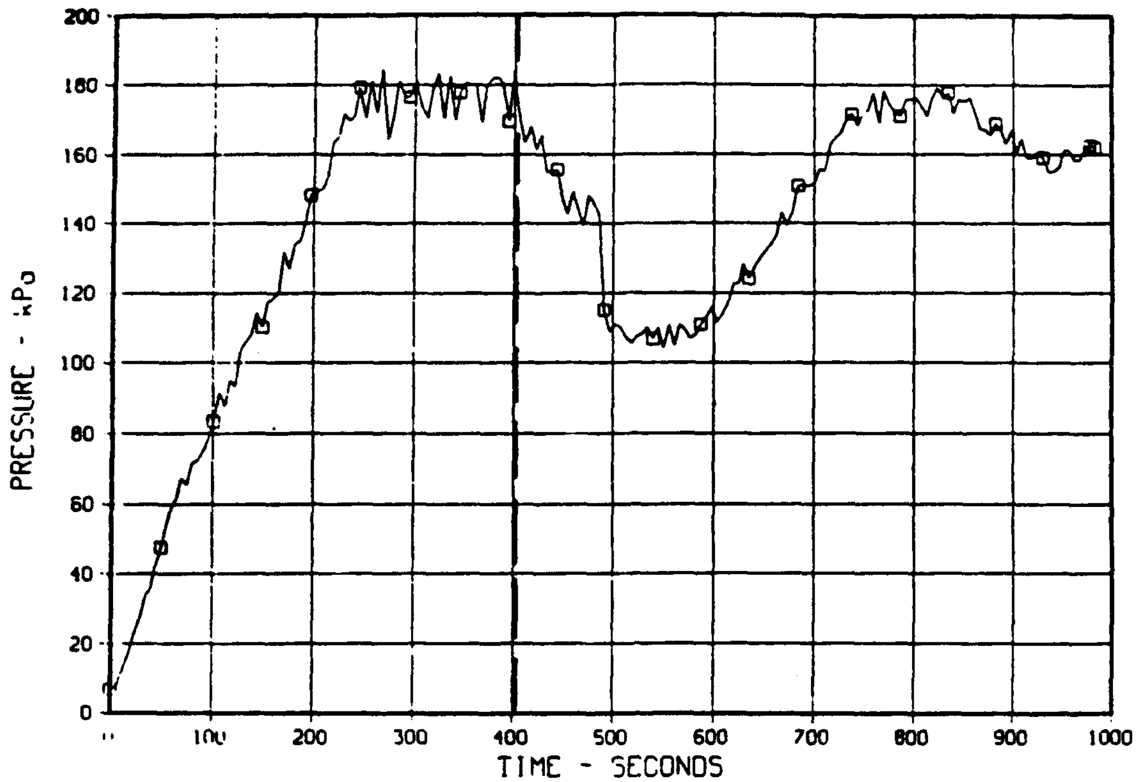


Figure 4-5. Pressure Profile for Test 2.0-6; GH_2 Pressurization of $TPLH_2$

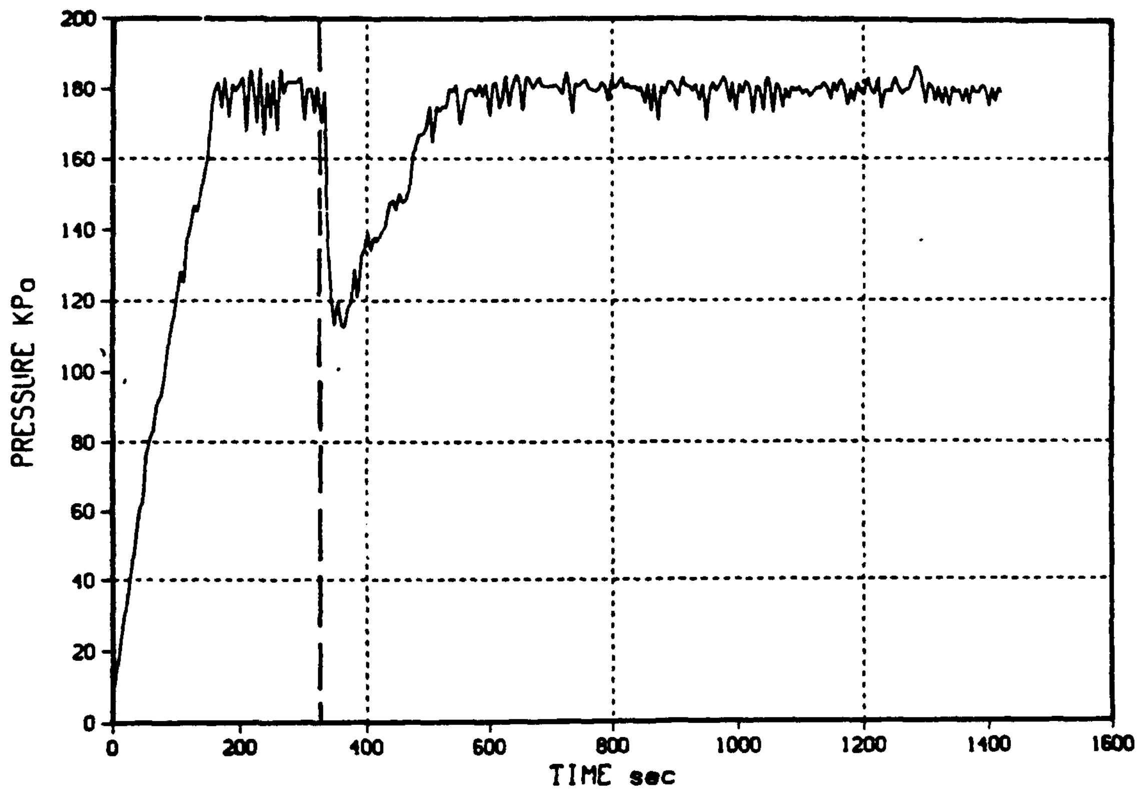


Figure 4-6. Pressure Profile for Test 2.0-17; GH_2 Pressurization of SH_2

The temperatures at various positions in the tank are shown for test 2.0-6 in Figure 4-7. Note that the sensor at 0.5 m (20 inches) is just above the liquid level; at the start of outflow, surging in the outflow line probably splashes liquid on T_{20} at about 485 sec causing it to chill to $TPLH_2$ temperature (although the initial drop in temperature may be due to condensation). This surging also is probably responsible for the severe pressure collapse seen in Figures 4-5 and 4-6, due to condensation of the GH_2 near the interface. The section on analysis, below, will describe the role of interface GH_2 condensation on the observed pressure collapse with the all-H_2 system.

The X-30 will probably use cold GHe for ground pressurization during loading, switching to GH_2 engine bleed for in-flight pressurization. Tests 2.0-7 and 2.0-8 used this method of pressurization, and the pressure trace for test 2.0-8 is shown in Figure 4-8. Note that when GHe was used for pressurization, it prevents the pressure collapse seen previously when GH_2 was used for pressurization. This is thought due to the cold GHe blanketing the interface and preventing the GH_2 condensation which causes ullage pressure collapse. The temperature distribution for test 2.0-8 is shown in Figure 4-9 and corroborates the GHe blanket thesis. Note that there is some cooling of T_{24} at initiation of outflow, due to cooling of the GHe blanket, but T_{25} [0.025 m (one inch) higher, but on another rake] is unaffected. These results were very encouraging because the presence of prepressurant GHe will apparently allow the use of efficient warm GH_2 in-flight pressurant without excessive pressure collapse from GH_2 condensation. This effect was to be explored further in the STF test program.

One of the primary objectives of the pre-STF testing was to gain experience working with slush hydrogen in medium/large quantities in order to better design the STF facility. Two instrumentation items identified as requiring modification as a result of the knowledge gained by the pre-STF tests are the addition of wall mounted temperature sensors and inlet gas temperature sensors mounted directly in the diffuser outlet. The wall mounted temperature sensors will provide wall temperature data that will enable more accurate determination of gas-wall heat transfer. The inlet gas temperature in the pre-STF testing was determined by sensors mounted in the lines prior to entering the diffuser with several feet of exposed line between the sensor and the test tank. Thus, the actual inlet temperature of the pressurization gas was difficult to ascertain. Evidence from the test data indicate that the GH_2 inlet temperature was approximately 150K while the GHe inlet temperature was approximately 120K, based on the convergence of the ullage temperature sensors to these values late in the runs as shown, for example, in Figure 4-7.

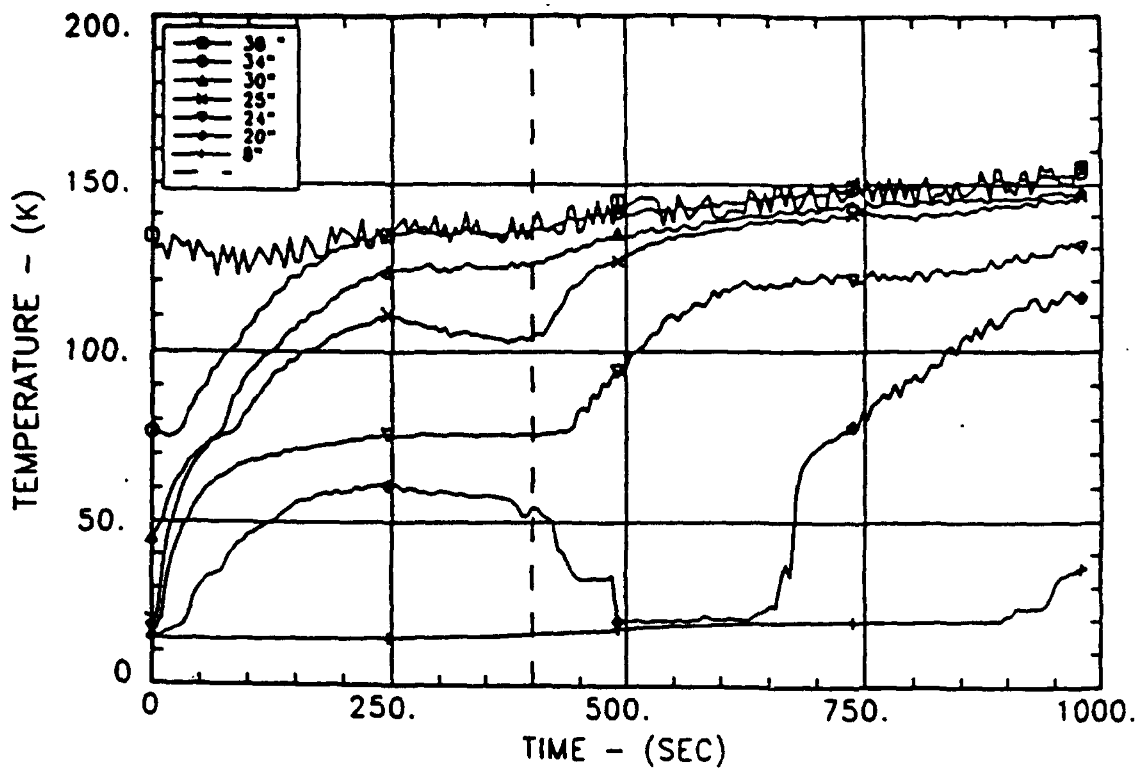


Figure 4-7. Temperature Profiles for Test 2.0-6; GH_2 Pressurization of $TPLH_2$

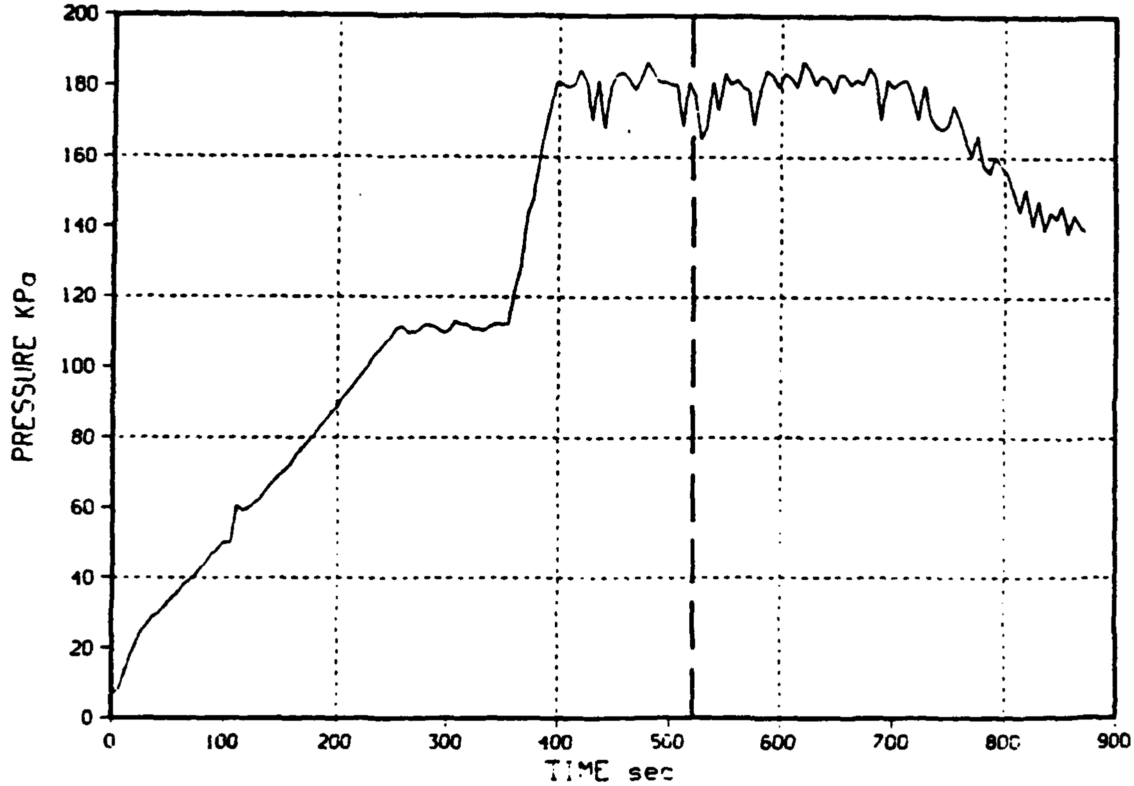


Figure 4-8. Pressure Profile for Test 2.0-8; GHe/GH_2 Pressurization of $TPLH_2$

4.1.2 Analytical Correlation of Pressurization Test Data

The MDA pressurization computer code, H431, was used to correlate and analyze the pressurization test data. Program H431 predicts the behavior of a propellant tank during prepressurization and/or expulsion with a heated pressurant, either propellant vapor or helium. Based on a one-dimensional model, the tank, propellant and ullage are divided into nodes and transfer processes are calculated between nodes to generate the time-variable thermal state of the system. The mathematical model permits an arbitrary tank geometry and a two-component ullage, and includes the effects of heat transfer between the gas and the tank wall and internal hardware. The program computes the time-dependent temperature and composition profiles, as well as the pressurant requirements. General tabular inputs are provided for material properties and initial and boundary conditions. The complete properties of the cryogens, including SH_2, are used in the code.

A comparison of the H431 prediction to the data from test 2.0-6 (GH_2 pressurization of $TPLH_2$) is shown in Figure 4-10. The GH_2 pressurization history is shown in Figure 4-11. With this pressurization rate, the pressurant velocities are very low; so low that natural convection in the tank ullage dominates the wall heat transfer processes. The prediction in Figure 4-10 assumes natural convection and interface heat transfer as shown in Figure 4-12. Note the large jump in assumed interface heat rate at 400 sec (commensurate with a large increase in effective interface area as a result of severe surging in the warm outflow line at the initiation of outflow). The interface heat rate (area) tapers off as surging ceases and approaches values assumed early in the test during prepressurization. The assumed GH_2 inlet temperature in Figure 4-10 is 150K, which results in the ullage temperature distribution prediction shown in Figure 4-13 (for 800 sec). The"flattening" of the observed temperature profile at about 0.3 m (one foot) from the tank top is not predicted by H431. This effect may be due to two- or three-dimensional circulation in the ullage. This effect clearly has only a minimal effect on the pressure prediction.

The results of H431 modeling of GHe prepressurization test 2.0-8 is shown in Figure 4-14. The GHe prepressurant temperature was assumed at 120K and the GH_2 pressurant temperature was assumed at 150K. Again, natural convection only was assumed during prepressurization, and no interface heat transfer was assumed during outflow from ~520 sec on. The very good agreement of the H431 prediction with the test data supports the contention that the GHe blanket at the interface prevents GH_2 condensation in the ullage resulting from surging of the outflow.

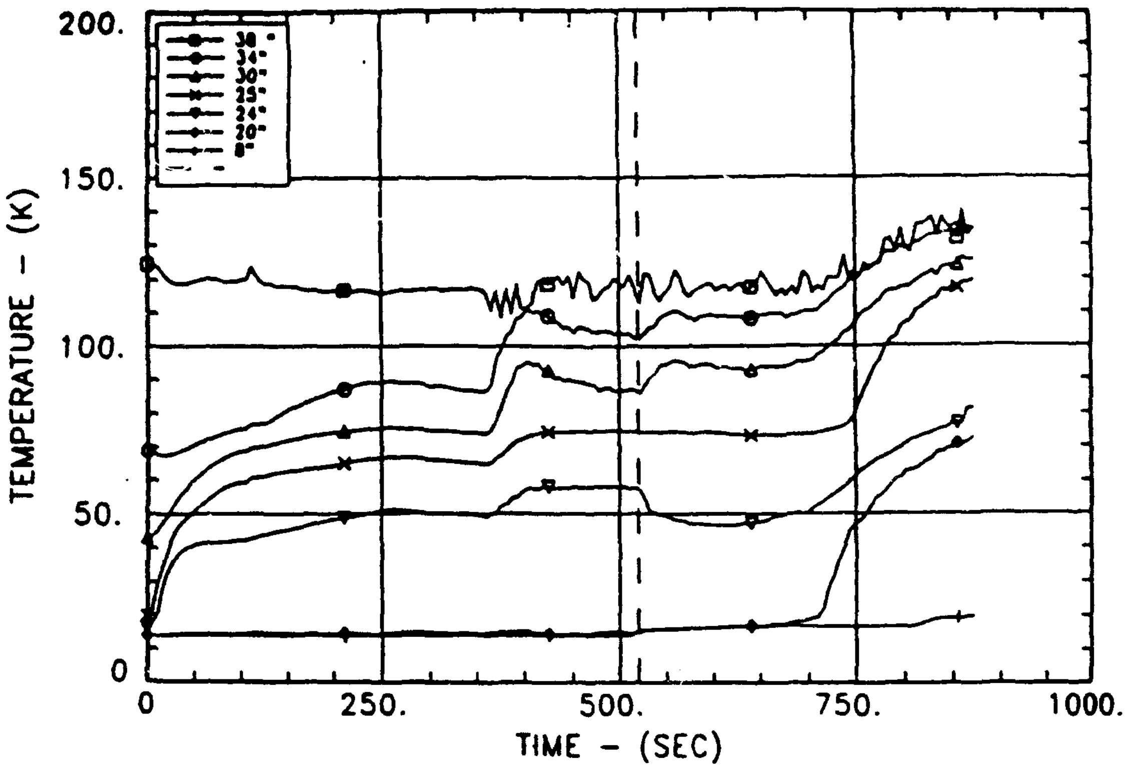


Figure 4-9. Temperature Profiles for Test 2.0-8; GHe/GH$_2$ Pressurization of TPLH$_2$

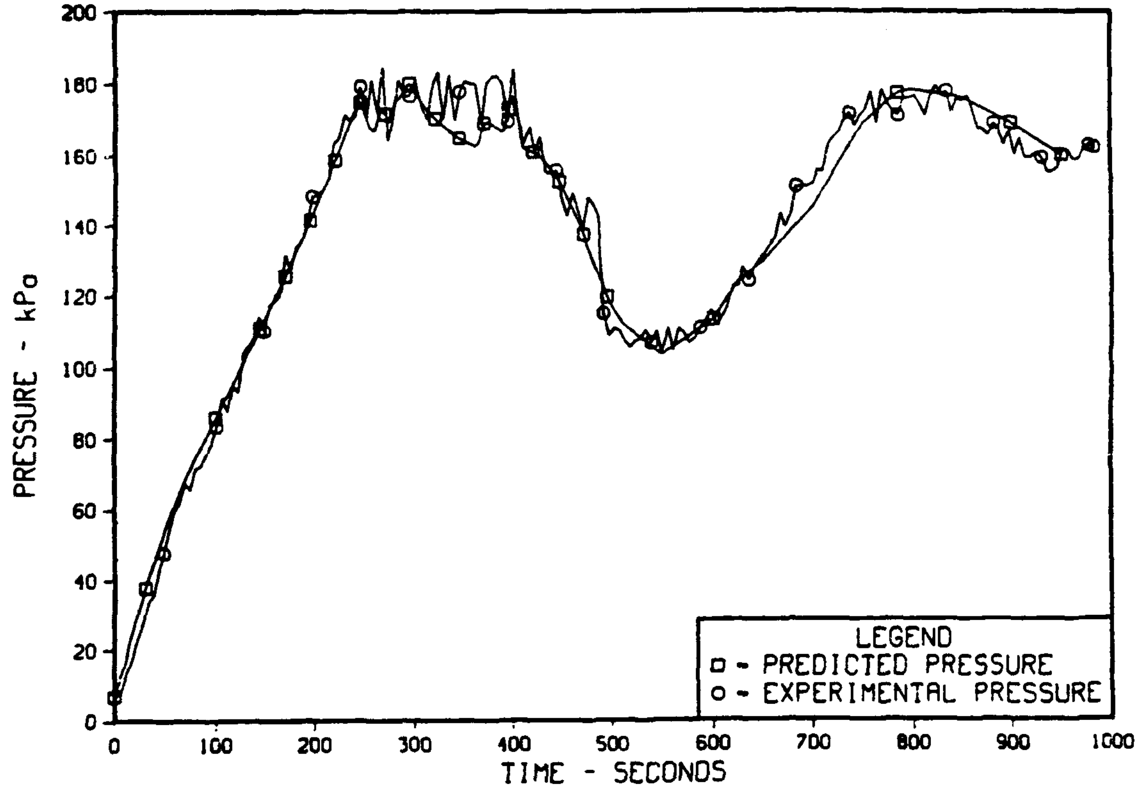


Figure 4-10. H431 Pressure Prediction Comparison for Test 2.0-6

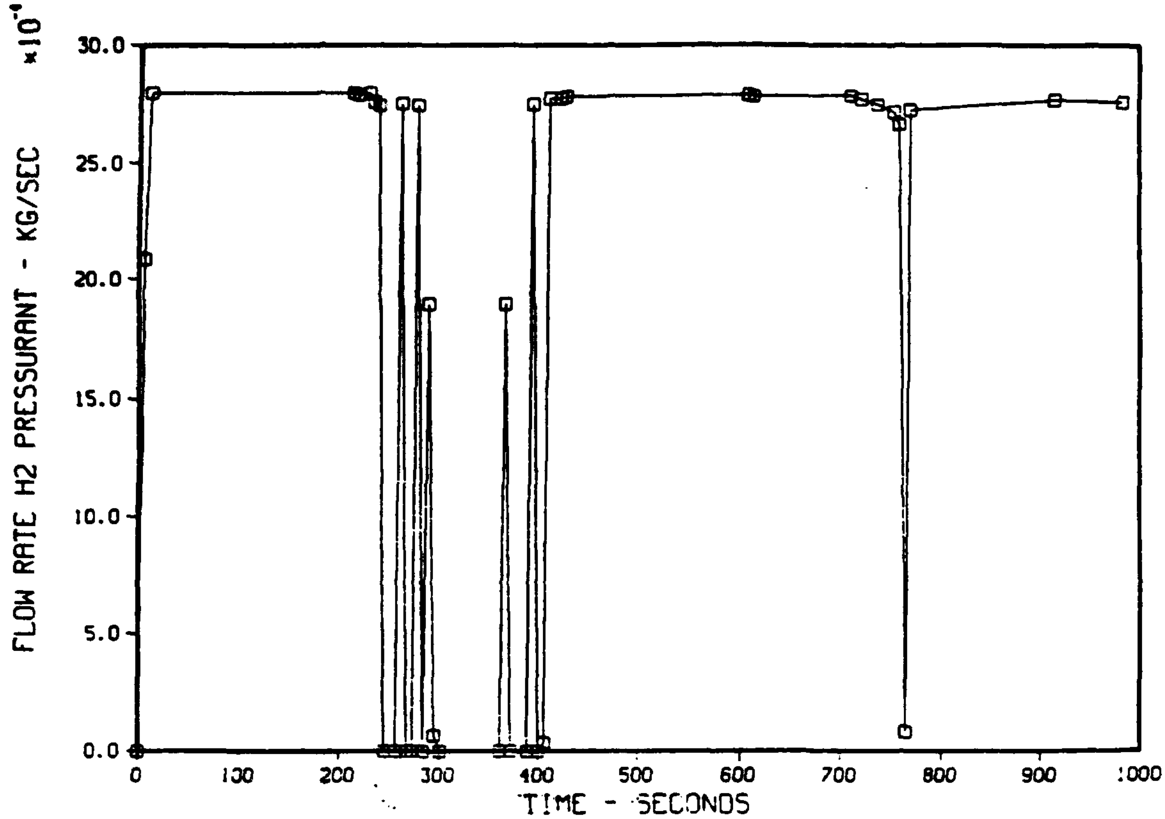


Figure 4-11. GH_2 Pressurant Flow History for Test 2.0-6

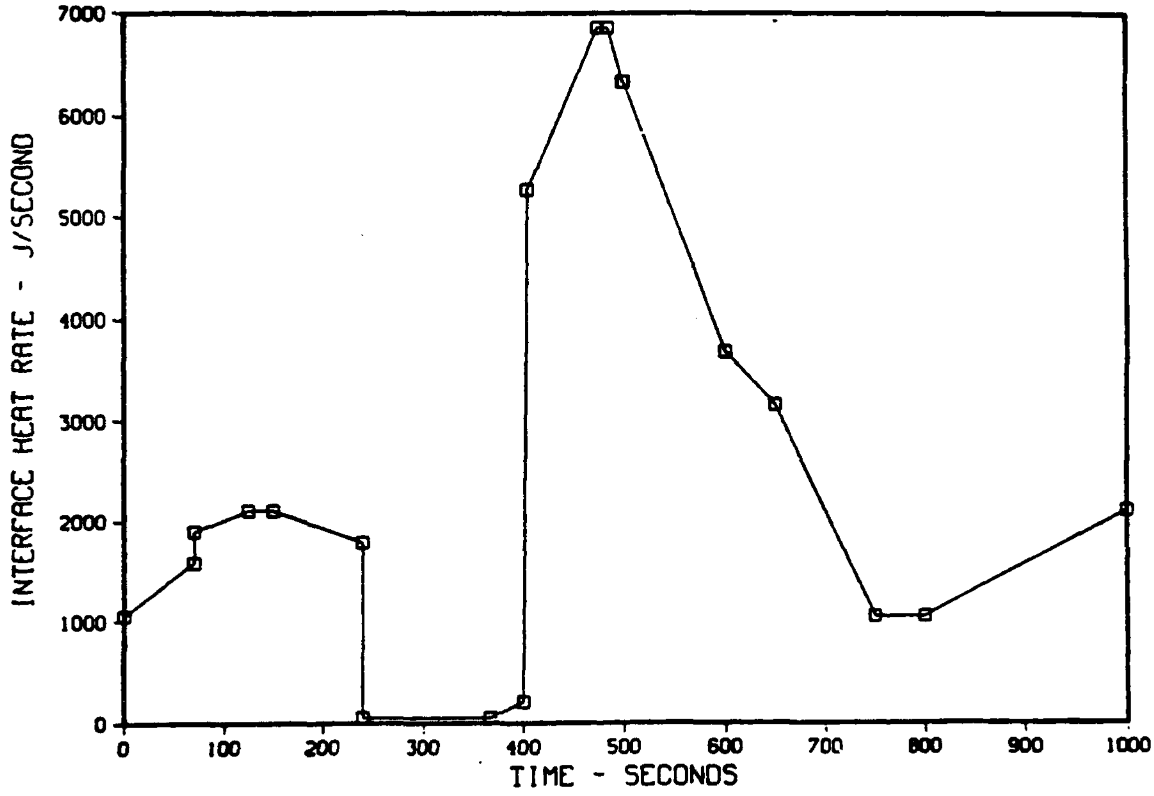


Figure 4-12. Interface Heat Transfer Assumptions for Test 2.0-6

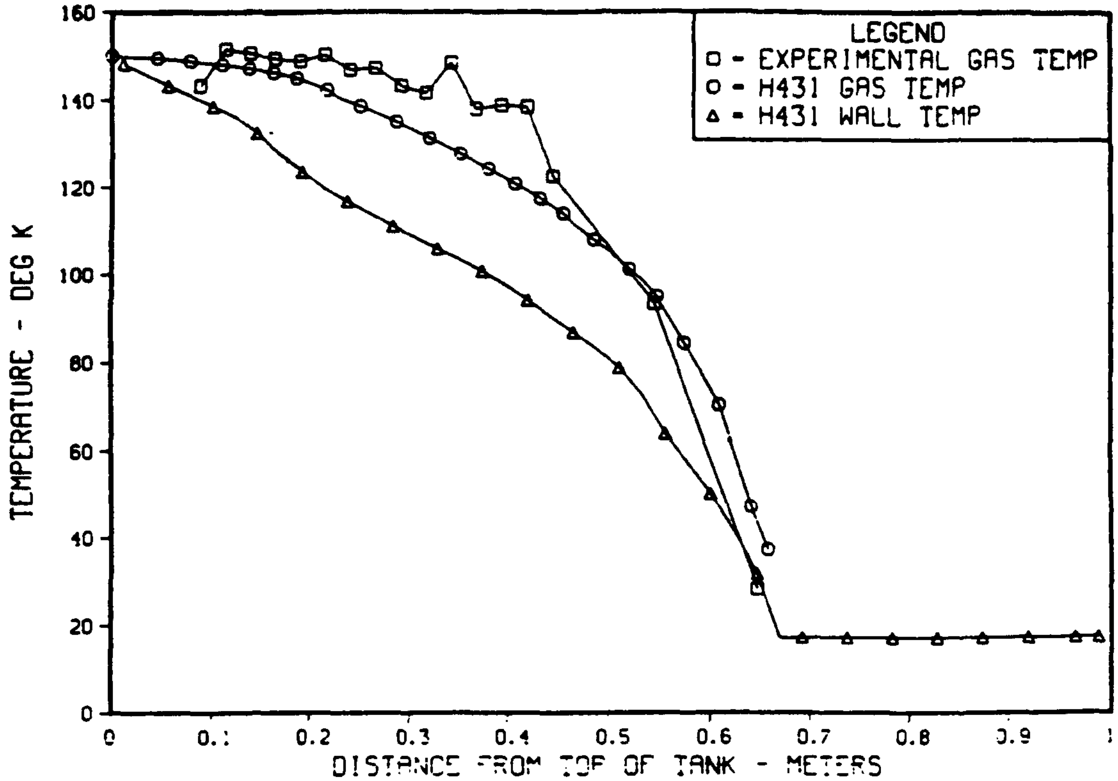


Figure 4-13. H431 Temperature Prediction Comparsion for Test 2.0-6

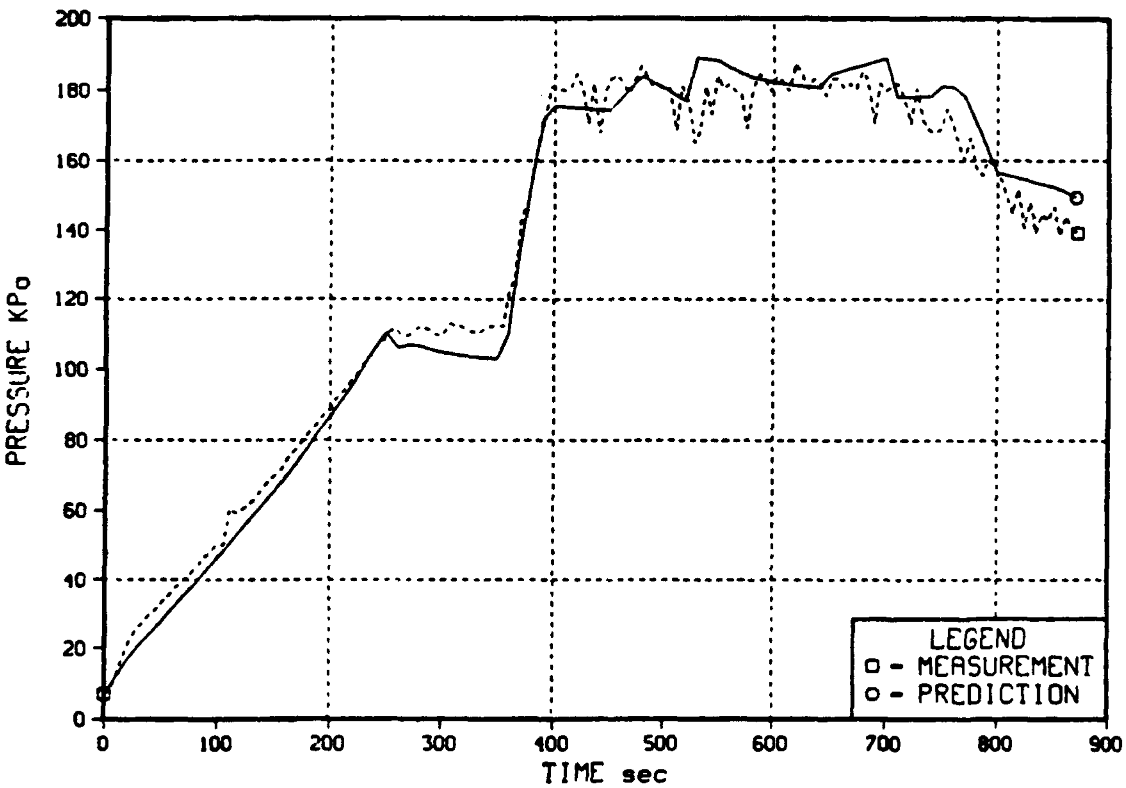


Figure 4-14. H431 Pressure Prediction Comparison for Test 2.0-8

4.1.3 Pump Test Results and Problems

A series of initial tests of the test tank submerged pump were performed to characterize performance. Following the initial pump tests with LH_2, the pump was examined and it was found that a phenolic bearing retainer had failed. The cause of failure was speculated to be water trapped in the pump. The bearings were replaced with units having steel retainers, which also failed. Following consultation with a retired JC Carter pump expert, the bearings were again replaced with reworked bearings with phenolic retainers. The rework consisted of reducing the number of balls in the bearings and increasing the web thickness of the phenolic retainers. The bearings and pump were carefully protected from moisture and contamination, and the repaired pump operated properly for the remainder of the program.

Pump tests were performed with both $NBPLH_2$ and $TPLH_2$ at various tank pressures [equivalent net pump suction pressures (NPSP)]. The flowrate versus speed data are shown in Figure 4-15 and efficiency is shown in Figure 4-16. Although there is considerable data scatter, the pump performance is the same for $NBPLH_2$ or $TPLH_2$ fluid and for various tank pressures, except for the obvious cavitation at 52.8 torr (1.02 psia) with $TPLH_2$.

To further understand the pump performance at the triple point (52.8 torr), tests were performed at various speeds to determine the cavitation point of the pump. Figure 4-17 shows that as little as 0.138 to 0.345 kPa (0.02 to 0.05 psi) of NPSP is needed to overcome the cavitation point. It appears, however, that at very low mixing speeds (< 7% pump speed), the pump will operate without cavitating. It is expected that most of the SH_2 production can be accomplished with the low mixing speeds.

The pump performance data also show that the pump, with a flow capacity of 0.05 m^3/sec (800 GPM), was very much oversized for the 1.9 m^3 (500-gallon) tank. The maximum pump speed which could be run was 50%. It is clear that operating the pump at low speed for STF testing will be very inefficient. However, this was an existing unit and the very tight NASP schedule precluded procurement of a more properly scaled pump.

4.2 Sub-Scale Tests at the STF

The objectives of the MMAG subscale testing at the STF were to be accomplished in two parts: 1) to develop a repeatable procedure for producing slush hydrogen with good solid fraction and handling characteristics; and 2) to demonstrate slush property measurement and unique functional characteristics. The part one objectives were accomplished through the test and evaluation of the effects of varying primary production parameters, i.e., production cycle, agitation and evacuation

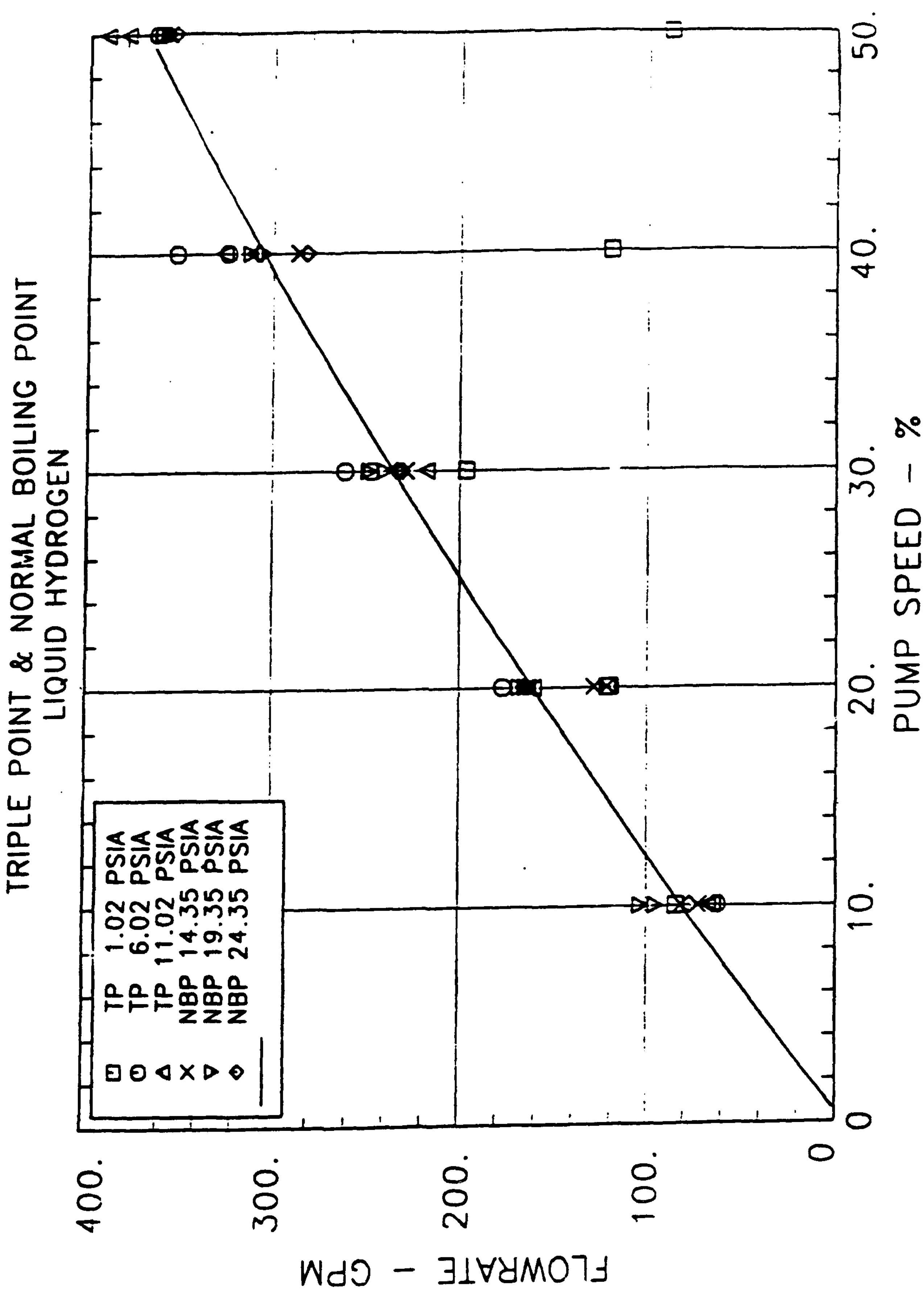


Figure 4-15. Flowrate vs Pump Speed

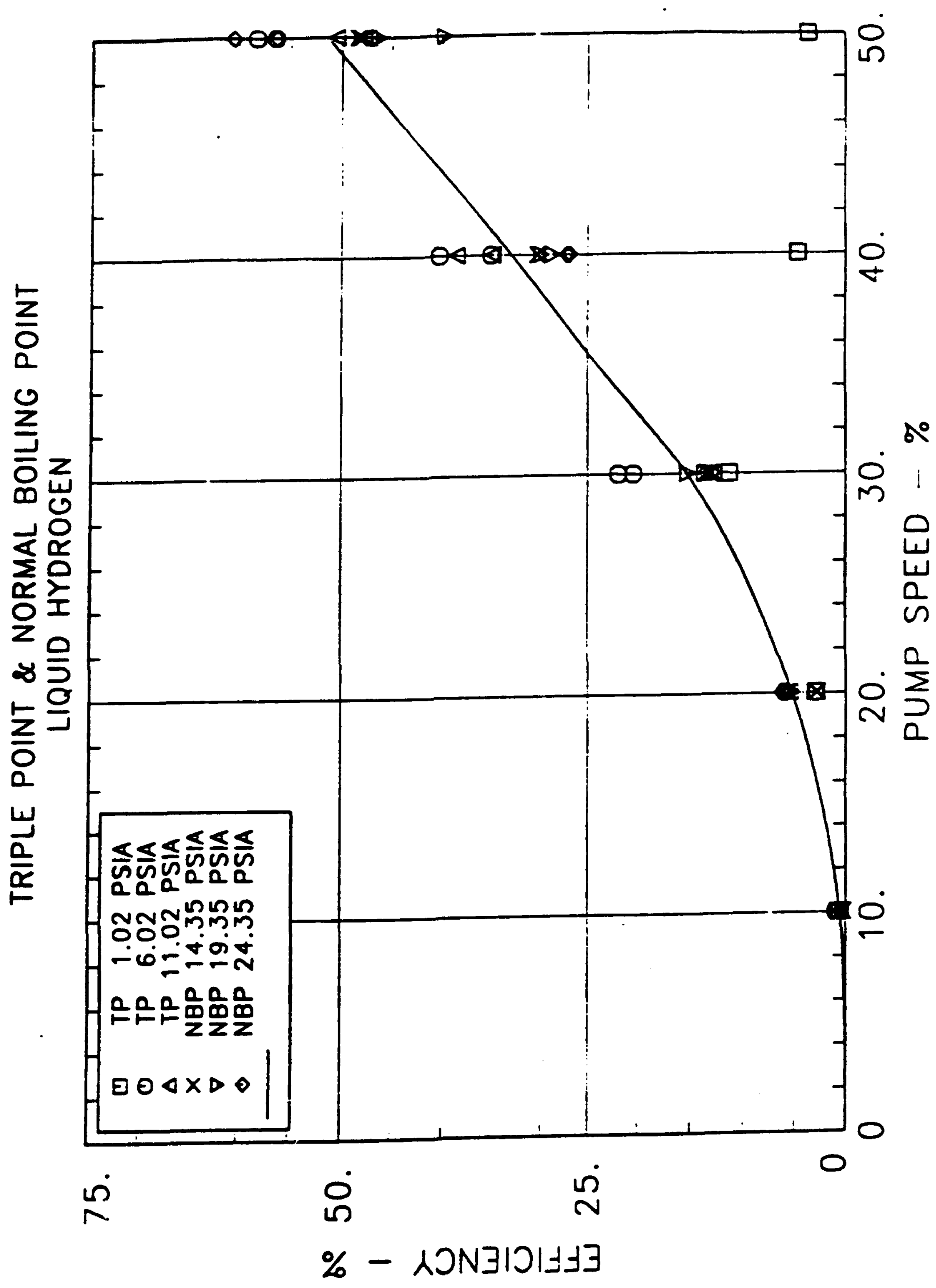


Figure 4-16. Efficiency vs Pump Speed

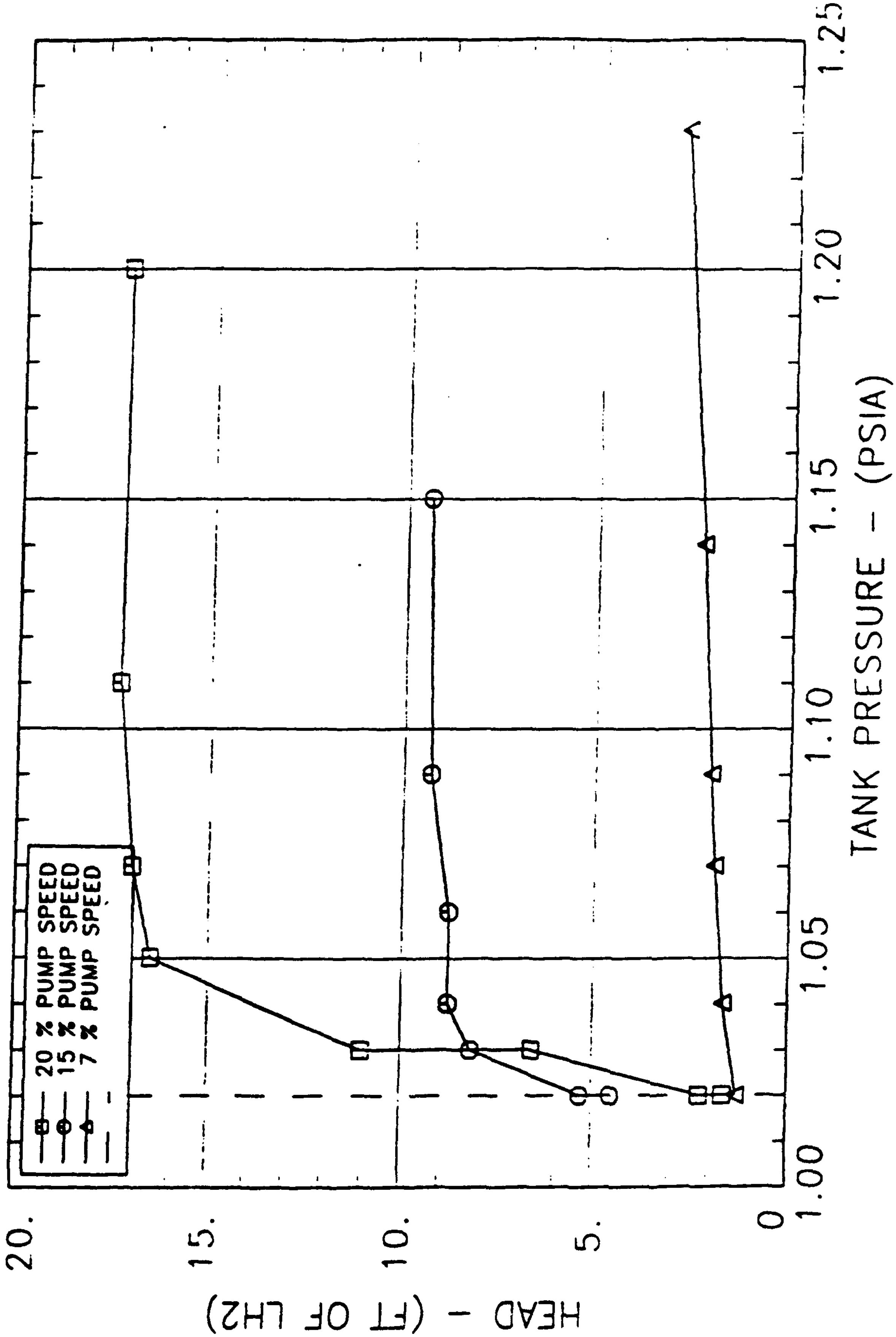


Figure 4-17. Head vs Tank Pressure

rate. The main goal was to achieve fresh unaged slush with a solid fraction of 25 to 30%. The slush should also have good handling characteristics exhibited by a non-agglomerated easy flowing mixture which does not accumulate on the slush production apparatus or instrumentation. In addition, the subscale test apparatus was to be used for checkout testing of various instrumentation items, as well as exploratory testing of recirculation injectors and other equipment.

4.2.1 STF Sub-Scale Test Facility Description

The subscale SH_2 test system, shown schematically in Figure 4-18, depicts the system in use at the Engineering Development Laboratory Hydrogen Test Facility at MMAG in Denver, Colorado. Flask 1, flask 2, the test section, and transfer piping are located inside of a three-walled test cell approximately 54 m by 6 m (176 ft by 20 ft) in size. The vacuum pump is a 0.424 m^3/sec (900 CFM) unit located about 9 m (30 ft) from the test cell. (This pump later became part of the STF three-pump vacuum system.) The flasks are single wall Pyrex glass about 1.22 m (48 inches) in length. Flask 2 is cylindrical with an ID of 0.262 m (10.3 inches), while flask 1 has an 0.457 m (18-inch) sphere fused to the 0.262 m (10.3 inch) diameter neck piece. The outer containers for each flask are stainless steel double wall dewars to provide insulation. The viewport for flask 1 is a 0.305 m (12-inch) circular window located at about the mid-line of the sphere. Flask 2 has two rectangular windows which provide a greater range for level visibility and measurement. The test section is a 2.54 cm (1-inch) vacuum jacketed glass section for visibility into the transfer flow stream. Flask 1 contains an instrumentation rake, an evacuation port and a mechanical stirrer. The second flask is a receiver tank for slush transported through the 2.54 cm (1-inch) transfer section. Early subscale pre-STF testing utilized only flask 1 which had been upgraded from earlier testing with improved multilayer insulation, improved instrumentation including silicon diode temperature sensors and germanium reference temperature sensors, improved jacket vacuum system, throttle capability for the vacuum evacuation, helium bagged lines and connections, and high resolution black and white video.

4.2.2 Sub-Scale SH_2 Production Testing

Preliminary testing and literature review indicated that the freeze-thaw production process was primarily controlled by four parameters. These were the evacuation rate and the parameters of the freeze-thaw cycle itself: evacuation time for each cycle, thaw time for each cycle and total time or number of cycles. Preliminary testing indicated that the agitation amplitude (mixer RPM) was also an important parameter which affected both the particle characteristics and the production cycle. It was also apparent that the variables had interactive effects on the slush production. In order to streamline the testing to a manageable amount, a matrix of tests was developed which could be analyzed utilizing statistical techniques. These techniques could evaluate the interactive effects as

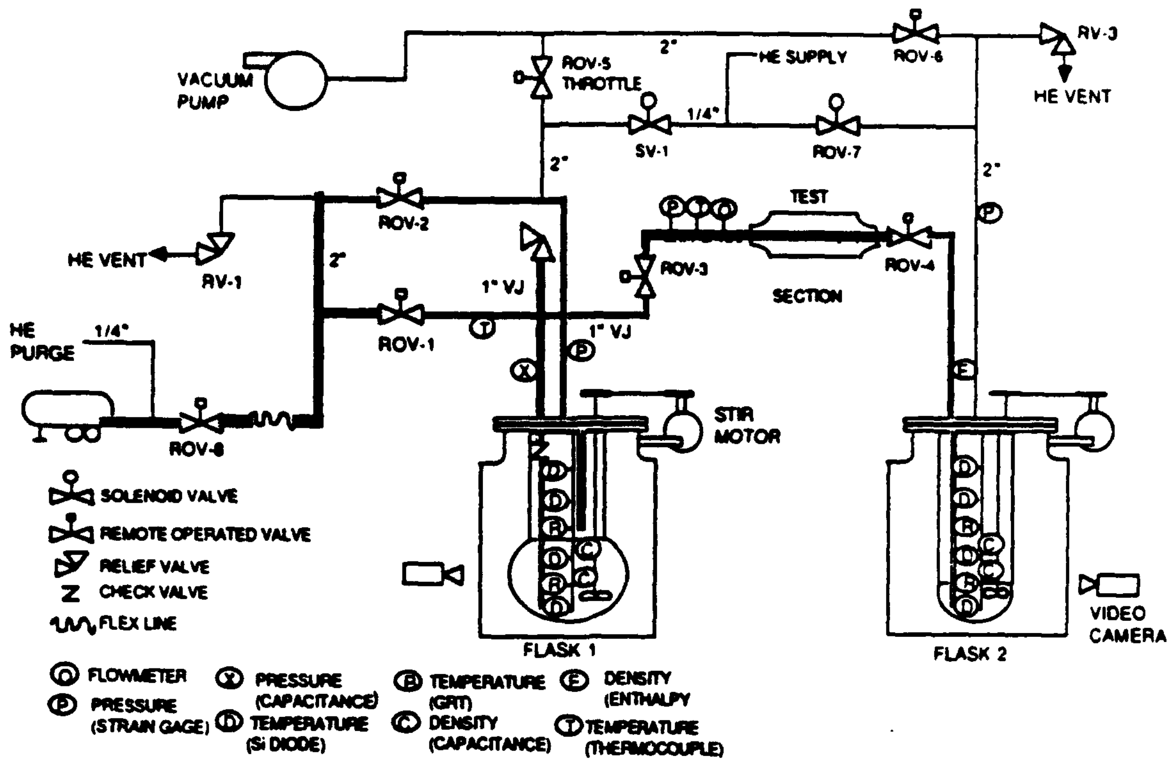


Figure 4-18. Sub-Scale Test Facility Schematic

well as single factor effects. The matrix included 27 test runs with each parameter varying among three values. Preliminary testing had indicated that these values would produce slush solid fractions in the 10-35% range.

As the testing proceeded through the first 11 runs, the slush solid fractions were not as high as expected. Evaluation of the single factor effects of each parameter on solid fraction showed rather inconclusive correlations. Review of the testing indicated several reasons for this and provided some clarifications. The pressure readings for some of the runs were in error and caused the cycle pressure to be higher than was specified. This had the effect of reducing the solid fraction for those runs. The lowest mixer RPM created sufficient agitation to keep the slush particles suspended while the increased levels caused a vortex "coning" effect. This vortex increased the surface area of the liquid and also increased the surface sloshing about the penetrations. Both of these increased the heat transfer rate between the liquid and the ullage gas and slowed the slush production process.

After evaluating the first 11 runs, it was decided to change the pressure transducer, eliminate mixer RPM as a parameter and run the mixer only at the low setting, and to establish a new test matrix for continued testing. By eliminating one parameter and testing with two point variables, an eight run test matrix was established. The results from this test matrix are summarized in Table 4-2.

Table 4-2. Series B Test Results Summary

Date	Run No.	Test Matrix No.	Cycle Time (sec)	Cycle Pressure (psid)	Run Period (series)	Evacuation Rate (%)	Mixer RPM	Solid Fraction (%)
12-08-88	PSTF14	1	1.5	.02	2	25	L	27
12-05-88	PSTF11	2	2.5	.02	2	75	L	23
12-05-88	PSTF12	3	1.5	.08	2	75	L	19
12-08-88	PSTF15	4	2.5	.08	2	25	L	12
12-09-88	PSTF16	5	1.5	.02	6	75	L	14
12-12-88	PSTF17	6	2.5	.02	6	25	L	11
12-13-88	PSTF18	7	1.5	.08	6	25	L	15
12-13-88	PSTF19	8	2.5	.08	6	75	L	18

These results show solid fractions up to 27%. Evaluation of the test parameters and data resulted in three additional tests, shown in Table 4-3, the final test of which resulted in a solid fraction of 36% (without aging). The basic cycle time results, (reported in Reference 2), together with experience from NASA-LeRC K-Site SH_2 tests (Reference 3) enabled us to define production parameters to be used in our future STF test matrix.

Table 4-3. Final Subscale Production Test Results

Date	Run No.	Test Matrix No.	Cycle Time (sec)	Cycle Pressure (psid)	Run Period (series)	Evacuation Rate (%)	Mixer RPM	Solid Fraction (%)
1-26-89		PSTF23	2.0	1.07	4	High	200	12
1-27-89		PSTF25	1.5	1.04	2	Low	200	22
1-27-89		PSTF26	1.5/9.0	NA	NA	High	200	36

4.2.3 Sub-Scale Testing of SH_2 Equipment

Pre-STF tests of bubble injection, capacitance densimeter and MDA enthalpy densimeter were also accomplished. The enthalpy and capacitance gages are critical to STF design, and testing was performed with LN_2 to assure minimum interference with the STF construction schedule. The

operational characterization with LH_2 was to be resolved in the future STF test series. The planned LN_2 testing was performed on the enthalpy gage and the Simmonds capacitance gage in the subscale test setup. The results are as follows:

1. All instruments were baseline tested with triple point nitrogen ($TPLN_2$).

2. Three batches of slush nitrogen (SN_2) were produced and transferred through the enthalpy gage and capacitance meter.

3. Following transfer, the SN_2 was melted back to determine the solid fraction.

4. Eight $TPLN_2$ outflow tests and three SN_2 outflow tests were performed.

The enthalpy gage, designed by MDA, has a 500 ohm wound resistance heater and a carbon resistor temperature sensor. The temperature (difference with triple point temperature), and hence enthalpy difference, for a given power input is proportional to the slush fraction. The device was installed on the outflow tube in flask 1 and immersed in the liquid/slush.

In pre-STF tests with SH_2 at MDA's test facility at Wyle, the enthalpy gage was calibrated with $TPLH_2$ and $NBPLH_2$. This calibration showed that the empirical proportionality factor was constant, as expected. In these tests, the gage was located at the pump outlet, and slush melting from the pump input power affected its reading. Therefore, in the STF design, a second gage was added to the pump inlet to better determine the actual in-tank slush fraction, as well as the effect of pumping on slush fraction degradation.

$TPLH_2$ tests of the enthalpy gage at the MMAG subscale test apparatus (Figure 4-19) resulted in correlation constants for the gage. The MDA enthalpy densimeter was installed on the inflow line to the spherical 0.076 m^3 (20-gallon) glass Dewar in the MMAG subscale test facility. This provided for submergence of the gage and clear viewing of the slush/fluid flow into and out of the Dewar. Using the correlation constants from the $TPLH_2$ tests, the slush fraction was determined for SH_2 tests (see Figure 4-20). The slush fraction was determined to be between 6% and 11%. These low slush fractions were assumed to be the result of the high heat leak into the subscale glass Dewars.

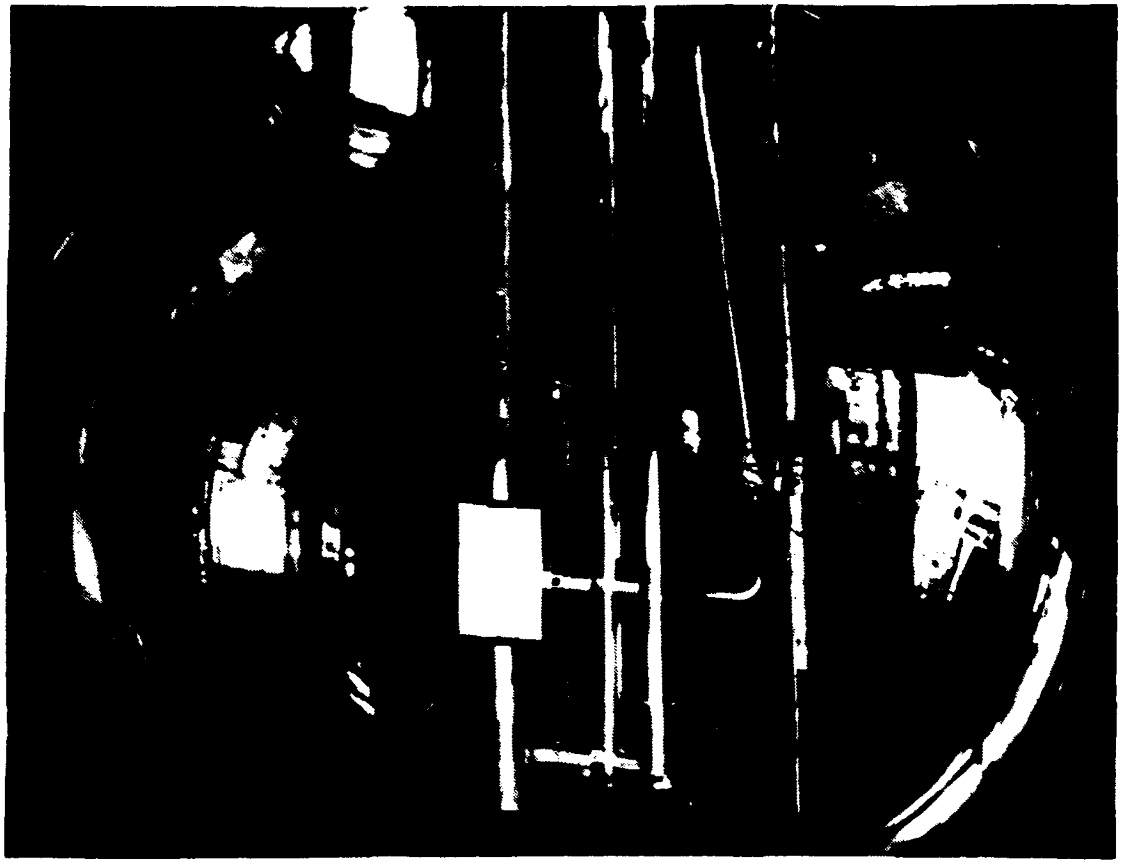


Figure 4-19. MDA Enthalpy Gage Test Setup

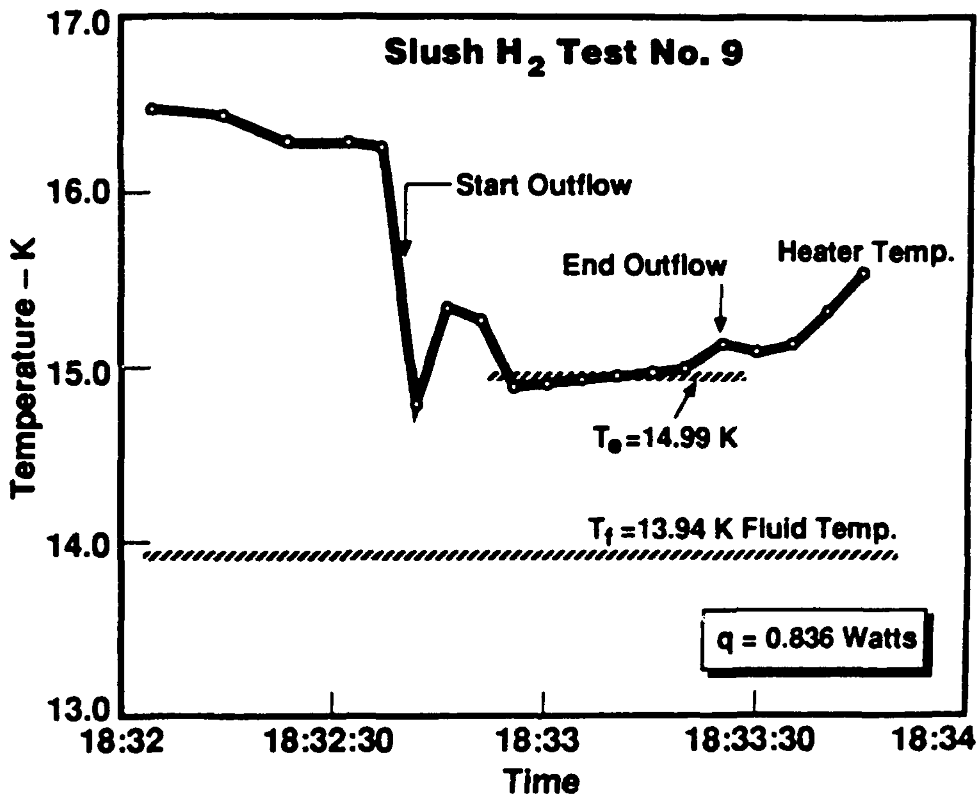


Figure 4-20. Slush Hydrogen Gaging Test

The Simmonds in-line capacitance slush fraction meter has concentric metal cylinders which make up capacitance plates and through which the flow is routed. Accurate measurement of the capacitance of the flowing fluid can determine the slush fraction. It should be noted that the dielectric constant of 60% SH_2 is only 1.7% higher than that of $TPLH_2$ (0% SH_2), hence very precise electronics are necessary.

Although this meter was designed for and installed in the NASA-MSFC SH_2 facility in the early 70's, it was decided that modified electronics would be necessary to accurately measure slush fraction. At the time of testing, the modified electronics were still under development by Simmonds; the test data reported were taken using electronics developed by MMAG as an interim measure. The meter was installed in the flow line between the two glass dewars and was insulated externally with foam and fiberglass insulation. The meter is designed to be submerged in the test tank during the STF tests.

The results of $TPLN_2/SN_2$ tests are shown in Table 4-4, and are inconclusive. Although the meter was chilled down with LN_2 prior to flowing $TPLN_2$ or SN_2 through it, the difference in $TPLN_2$ or SN_2 is not apparent. It is suspected that the SN_2 may have been melted prior to reaching the meter. This problem should not occur during tests where the meter is submerged in the fluid.

Table 4-4. Capacitance Meter Test Results (Picofarads) in N_2

Date	Normal Boiling Point*	Triple Point	Slush
8-2	120	133	
8-3	122	133	
	117		132
	123	130	
8-4	122		133
8-9	124	133	
	122	132	
	122	133	
8-11	123	131	
	124		131
	120	134	

* During chill down of transfer line

The originally planned bubble injection tests were to study the collapse of warm GH_2 in SH_2 or $TPLH_2$ in order to verify analytical predictions and explore critical injection parameters for the recirculation process prior to testing in the STF. In order to avoid interference with STF construction, the tests were revised to study injection of warm GN_2 into $TPLN_2$. $TPLN_2$ was selected instead of SN_2 for visibility in the subscale glass dewars. It is anticipated that bubble collapse in slush should be as fast or faster than in triple point liquid.

Our analysis for condensation of vapor in a bubble within triple point liquid, and that of Reference 4, indicates that small bubbles [of the order of <2.5 mm (0.1 inch)] will collapse in about 10^{-3} seconds. In our test, GN_2 was injected into $TPLN_2$ at 186.87 actual cubic centimeters per second at 37.9 kPa (5.5 psia) and 292K (66°F) through two 0.76 mm (0.03-inch) holes. The estimated injection velocity inside the flask was about 15 m/sec (50 ft/sec) at the local conditions. The injection process was observed on video and recorded on videotape. The bubble stream vanished in about 2 cm (0.8-inch), or a collapse time of about 10^{-3} seconds.

4.3 Planned STF Operation for the Initial Technology Tests

Several series of tests were planned to be performed in the STF located at the Martin Marietta Propulsion Laboratory in Denver, Colorado. The scope of the testing was to provide data that are essential to determining the feasibility of using SH_2 as a fuel for the X-30. The initial series of tests were to determine baseline data on SH_2 production, aging, loading, upgrading, SH_2 maintenance, expulsion (pressurized and pumped) and gaseous hydrogen (GH_2) recirculation. This initial test series was based on the test series (modified "55 tests") planned for Task II of this contract as modified by the national NASP team in meetings held in January 1991. These current modifications represent the test emphasis resulting from the NASP teaming which occurred in 1990.

The STF testing is divided into six sections: production, aging, loading and upgrading, pressurized expulsion and transfer, pumped expulsion and transfer, and warm GH_2 recirculation. The relationship between these tests, and their sequencing, is shown in Figure 4-21. As can be seen, in general for each test day, SH_2 is produced in a batch, goes through aging, is expelled from the SH_2 generator for loading/upgrading into the test tank, and is then used for either pressurized expulsion (4.xx) or pumped expulsion (5.xx) from the test tank, or recirculation (6.xx) within the test tank. The general flow and top-level procedures for these tests are shown in Figure 4-22. Detailed STF flow loop setup and procedures were developed for each test series. Future subsequent test series were planned to explore other development issues, such as jet-entrainment-mixers, spraybars, and gaging arrays.

4.4 LN_2 Checkout Tests at the STF

The initial STF checkout tests involved LN_2 checkout of the slush generator, test tank, triple point tank and transfer system. The activities within the slush generator were observed with high-resolution video and recorded on videotape. Illumination and viewing within the slush generator were excellent.

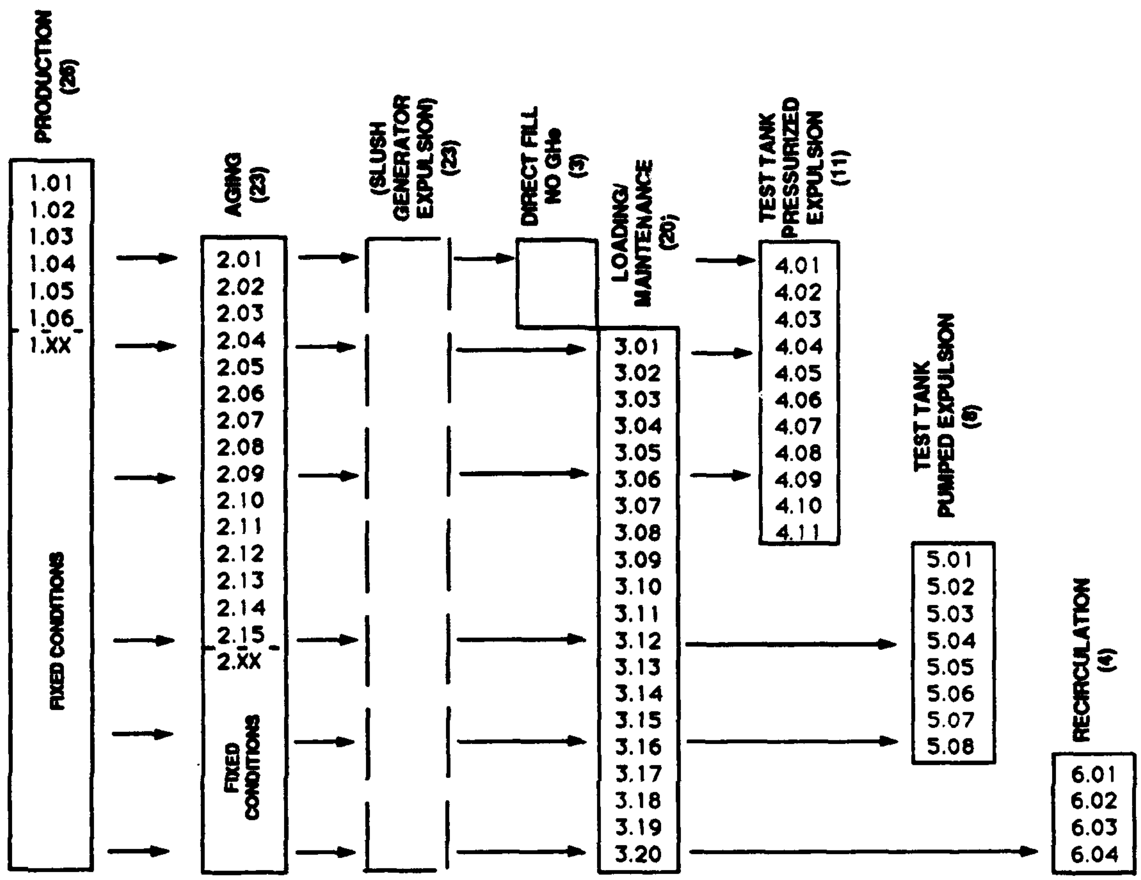


Figure 4-21. Test Matrix Sequencing

The slush generator was loaded with about 3.8 m^3 (1,000 gallons) of LN_2. The diode temperature sensor rake appeared to work properly. The capacitance level sensor was calibrated for LN_2 and the NRA densimeter was not hooked up for this test. The stirrer in the slush generator was operated and run up to 35% speed before settling on 20% speed (50 RPM) for pumpdown to triple point. The evacuation heater (to protect the vacuum pumps) is sized for slush production (at about 53 torr - 1 psia) and is overpowered during the high flow on the initial pumpdown. Therefore, the pumpdown process was slowed, and took about 1.5 hours to reach triple point from NBP.

During pumpdown, one of the three vacuum pumps experienced overheating and excessive motor power draw. The bearings were suspected and this pump was carefully watched and occasionally shut down during the slush making process. It was repaired prior to SH_2 testing.

The stirrer was set at 30% speed (75 RPM) and the vacuum control valve set at 10 sec open and 15 sec closed. The automatic slush production cycle was run for about one hour and produced

visually high quality slush. The mixer and slush making were stopped and the slush allowed to settle. It settled so that there was about 0.6 m (24 inches) of $TPLN_2$ on top of 2 m (~80 inches) of settled SN_2.

An attempt was made to transfer SN_2 to the test tank and triple point tank. This could not be accomplished due to blockage in the outflow line possibly caused by trapped moisture in the dead-ended section of line to the sample bottle (which was yet to be installed). Warm GN_2 purging past the blocked area melted the blockage and allowed dumping of the LN_2.

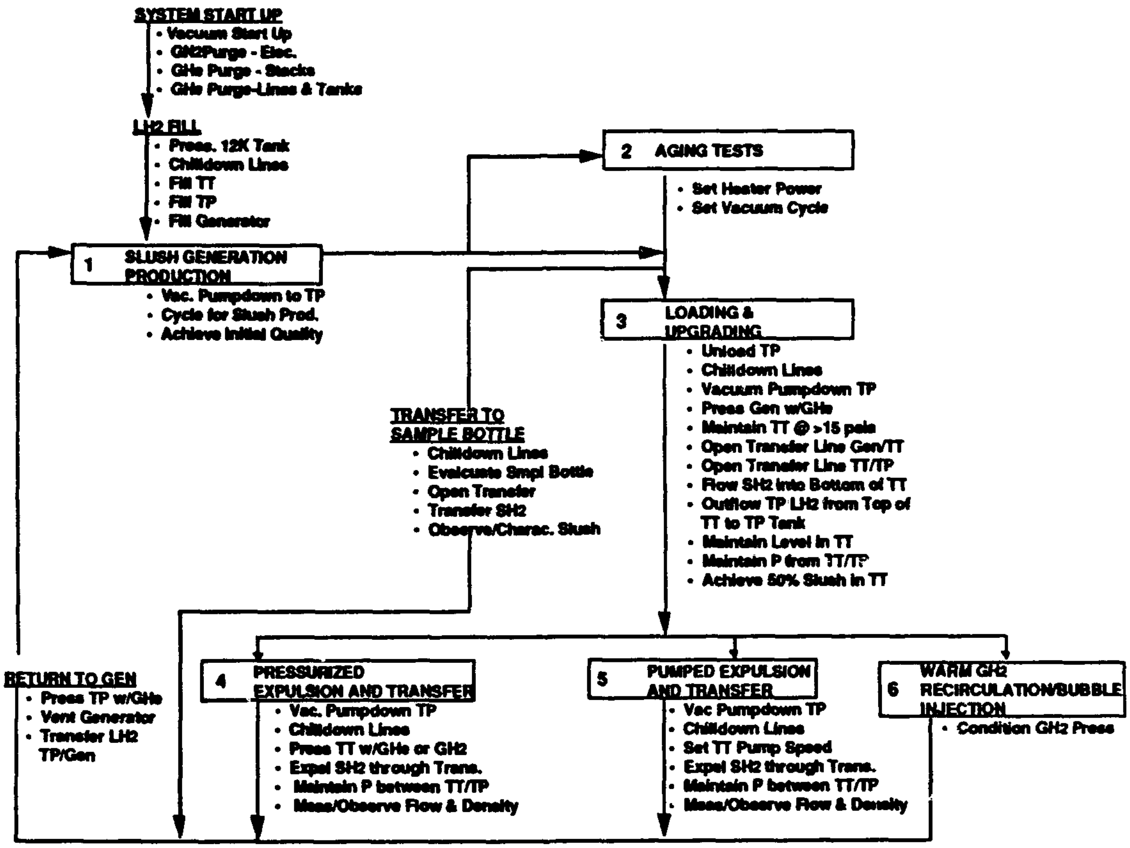


Figure 4-22. Overall STF Operational Procedure

Future plans for the STF included a second LN_2/SN_2 checkout test in late October 1989 in which SN_2 was to be produced, aged, transferred to the sample bottle, and to the other tanks and transfer section in accordance with the test procedures planned for SH_2 testing. However, due to the tight schedule and attempts to proceed quickly to LH_2 tests, this additional LN_2 testing was not performed. The final Test Readiness Review was held on 1 November 1989, followed shortly thereafter by the final helium mass spectrometer leak check. Although at this point the STF was ready to proceed to the LH_2 checkout and test series, the program was shut down as described previously in Section 1.0.

5.0 DISCUSSION OF RESULTS

The design, fabrication, and assembly of the STF was successfully accomplished within extreme schedule and cost constraints which were typical of the early NASP program. The resulting STF is a flexible, high technology facility capable of performing a complete spectrum of SH_2 testing (Figure 5-1).

Early pre-STF tests, performed in the MDA test tank at Wyle Labs, showed the critical nature of GHe pre-pressurization of SH_2 to avoid pressure collapse during expulsion. Further tests isolated and resolved SH_2 pump bearing problems, validated SH_2 solid fraction gage operation, and demonstrated the parameters of SH_2 production in small scale apparatus.

The STF was subsequently used for SH_2 testing under the NASP consortium, and could have performed this testing under this contract except for the change in NASP program emphasis and cancellation of the Technology Maturation Program following NASP teaming.

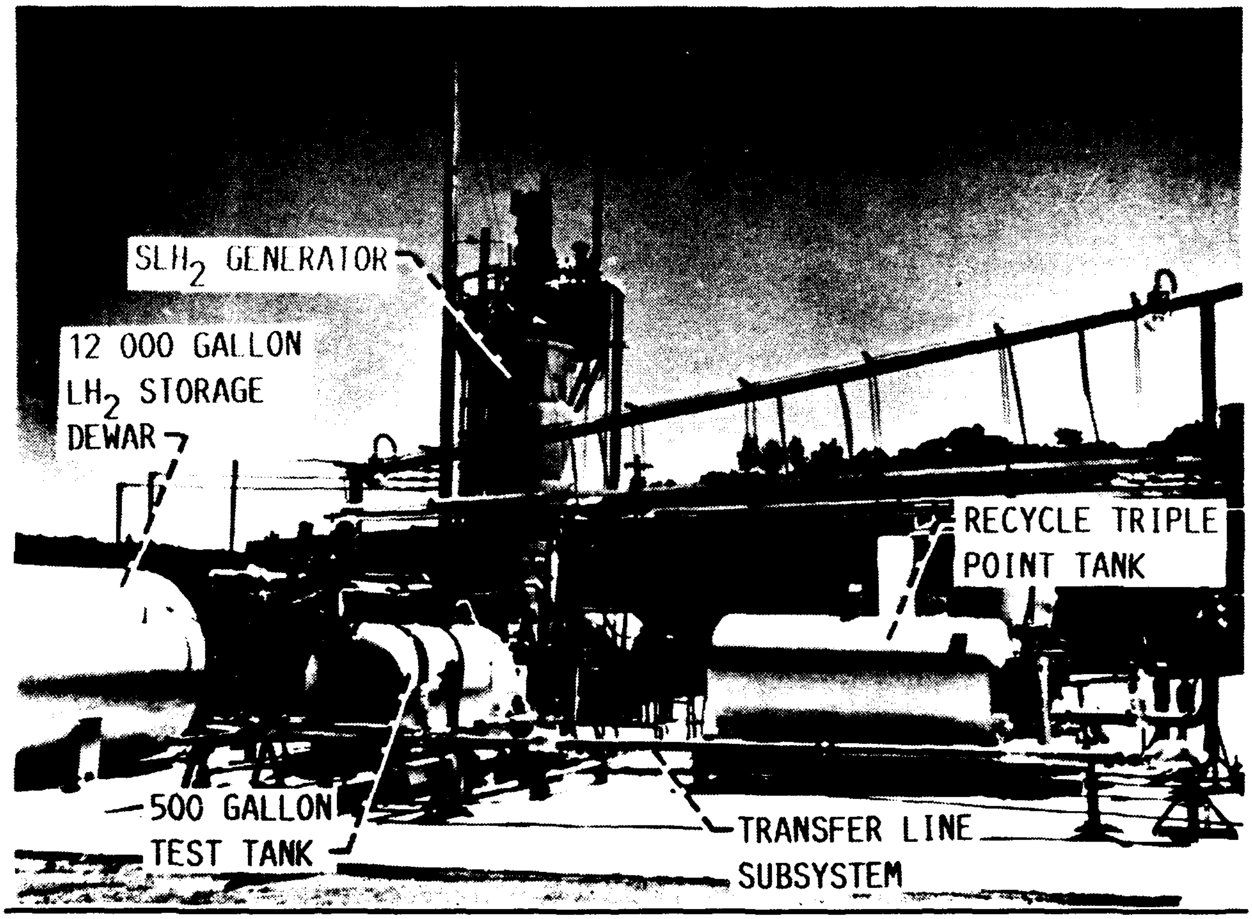


Figure 5-1. Overall View of the STF

Many innovative ideas were included in the STF design including:

- A full-scale slush generator using the freeze-thaw batch process, and adaptable to continuous production.
- A large-scale test tank with a submerged SH_2 pump to simulate the NASP vehicle.
- Successful use of nuclear radiation attenuation (NRA), enthalpy, and capacitance gages, designed for SH_2 application, to measure SH_2 solid fraction.
- Successful use of a sample bottle and transparent transfer line segments for viewing SH_2 as well as video coverage within the slush generator and test tank, which resulted in excellent viewing of the SH_2 production [illegible] and transfer processes.

6.0 CONCLUSIONS

The STF is a unique combination of NASA-supplied equipment, MDA-supplied equipment, and MMAG-supplied equipment to allow fabrication of a $7 million SH_2 facility for a Government cost of about $4 million. Development of this facility is an excellent example of Government-Industry cooperation in achieving cutting-edge technology under a very tight schedule.

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13. ABSTRACT *(Maximum 200 words)*

A slush hydrogen (SH_2) technology facility (STF) was designed, fabricated, and assembled by a contractor team of McDonnell Douglas Aerospace (MDA), Martin Marietta Aerospace Group (MMAG), and Air Products and Chemicals, Inc. (APCI). The STF consists of a slush generator which uses the freeze-thaw production process, a vacuum subsystem, a test tank which simulates the NASP vehicle, a triple point hydrogen receiver tank, an transfer subsystem, a sample bottle, a pressurization system, and a complete instrumentation and control subsystem. The STF was fabricated, checked-out, and made ready for testing under this contract. The actual SH_2 testing was performed under the NASP consortium following NASP teaming. Pre-STF testing verified SH_2 production methods, validated special SH_2 instrumentation, and performed limited SH_2 pressurization and expulsion tests which demonstrated the need for gaseous helium pre-pressurized of SH_2 to control pressure collapse. The STF represents cutting-edge technology development by an effective Government-Industry team under very tight cost and schedule constraints.

14. SUBJECT TERMS

Slush hydrogen testing; Liquid hydrogen facility; Cryogenics

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